EVALUATION OF STRATEGIC LIFT:

A RESPONSE SURFACE METHODOLOGY

FOR THE MINOTAUR MOBILITY MODEL

THESIS

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Preface

This thesis explores the possible uses of the MINOTAUR mobility model in evaluating strategic lift. Specifically, a response surface is developed for MINOTAUR which examines the effects of varying levels of aircraft and mobilization warning time on strategic lift. Four aggregate measures of effectiveness are proposed and tested for validity.

Multivariate analysis is used to explore the true dimensionality of the four aggregate MOEs as well as twelve other model output measures. Assessments are made as to the underlying factors which give rise to the measures of effectiveness, and the validity of those measures.

Completing this work would not have been possible without the support of great ENS faculty members, and I would like to thank them. To Lt Col "Skip" Valusek, for providing support and for being an outstanding class advisor; To my reader, Major Mike Garrambone, for passing his energy, enthusiasm, and passion for excellence on to others; and to Major Ken Bauer, my thesis advisor, for his insights and ideas, and his patience in entertaining my sometimes incoherent questions.

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I. INTRODUCTION

> US force projection capability — an aggregate measure that includes airlift, sealift, and pre-positioned equipment, munitions, and supplies — has roughly doubled since 1980... But that progress is still insufficient... General Duane H. Cassidy, Commander in Chief of US Transportation Command, told the Senate [in April 1988] that "we simply do not have enough airlift or sealift, nor are we closing the gap..." (Correll:38-40)

Historical Perspective

US defense commitments for our allies (especially NATO) in non-nuclear conflicts require enormous amounts of men and material to be moved rapidly to reinforce our forward based forces. To make a timely initial response possible, a reliance on airlift support is an absolute necessity. Sealift, as an alternative, although possessing considerable capacity, is very limited in its ability to deliver goods on short notice (Matarese:1).

At first glance, it seems a large scale conventional war in Europe would tax the airlift system most heavily. This is due to several factors, including the close proximity of the Warsaw Pact forces, their large number of forces, and the large ratio they enjoy over the current NATO forces in place to oppose them. To allow lower peacetime manning and

budgets, the strategy is to have a large "swing" force of deployable US men and resources which could move rapidly enough into Europe to reinforce troops in-country faced with a Warsaw Pact offensive. As a result of the threat, the US has committed to delivering 6 Army divisions, 60 Air Force fighter squadrons and a Marine amphibious brigade to Europe in 10 days (Record:91). Since sealift cannot load, haul, and off load the men, supplies, and equipment needed in Europe in less than about 15 days, the entire trans-Atlantic logistic commitment for the first 10 days falls upon airlift (Matarese:1).

A swing strategy using mobile forces and the execution of that strategy are radically different entities. A prime example of the problems associated with mobilizing US forces occurred during the NATO Nifty Nugget exercise of 1978. In October of that year, the federal government conducted its first full-scale simulated mobilization exercise in 30 years. The scenario involved deploying 400,000 troops to Europe in response to a conventional attack. The exercise was a combined effort between 24 military organizations and 30 civilian agencies (Correll:38-39).

The exercise rapidly deteriorated into chaos. The troops ran out of critical types of ammunition and were "killed" in the first few weeks. When the exercise ended after 21 days, many of the sealifted supplies were afloat in the Atlantic or still sitting in US seaports. Equipment to be airlifted was also running behind schedule, despite

augmentation of active duty forces by the reserves and commercial airliners. Outsize cargo requirements, those needing a wide-body cargo transport such as the C-5 Galaxy, were roughly ten times what Military Airlift Command (MAC) could deliver.

Shortage of cargo movement capability was not the only problem, however. Mobilization planning problems were also significant. In one particularly bad case MAC received 27 validated requests to move a particular military unit to 27 different locations (Correll:38).

As a result of the after action-reports of Nifty Nugget and other exercises, concerns regarding strategic lift were addressed by the US Congress in the Defense Authorization Act of 1981 (Ulsamer:58). This in turn generated the Congressionally Mandated Mobility Study (CMMS) of April 1981. This study examined lift requirements for four different baseline scenarios: An invasion of Saudi Arabia, an invasion of Iran, an invasion of NATO, and an invasion of Saudi Arabia followed by an invasion of NATO. The measure of airlift capability used was the daily rate of movement of tons of cargo (or passengers) over miles travelled, usually referred to as millions of ton-miles per day (MTM/D). The measurement has cargo moving from peace-time storage locations to war time need locations. The study found the requirement approached 150 MTM/D, assuming minimal pre-attack warning for mobilization (Leary:81). Later, a fiscally constrained figure of 66 MTM/D was agreed to as a

goal to be met by the year 2000 (Coyne:1985). The existing airlift capacity in 1981 was less than 30 MTM/D.

Following the CMMS, the Air Force created the USAF Airlift Master Plan in September 1983. Its purpose was to establish milestones to achieve the 66 MTM/D goal. The plan had two stages. The first stage, to be completed by FY 1988, used a target of 48.5 MTM/D. This was to be accomplished by the acquisition of additional C-5 cargo aircraft, the purchase of KC-10 refueling / cargo aircraft, an increase in aircraft in the US civil reserve air fleet, and maintenance of the present strategic airlift fleet. The second stage, to be accomplished by 1998, brought the capacity up to 66 MTM/D by acquiring new C-17 cargo aircraft and placing a number of active duty C-130 and all C-141 airframes in Air Force Reserve units (Cassidy:120, Leary:82, Ulsamer:59).

While strategic airlift seems to be headed in the correct direction, sealift still faces significant problems. No target sealift capability corresponding to the 66 MTM/D airlift target exists for sealift (Roehrkasse).

Additionally, the maritime industry that could support a large scale overseas military operation is in a state of decline. An author paraphrasing General Cassidy (then CINC TRANSCOM), noted

> Since 1980 the US flag commercial fleet has declined from 843 active ships to 369. By the year 2000, there will be only 220. Domestic shipyards have not begun work on an American flag vessel since 1985, and no merchant ships are presently under construction in US shipyards. The merchant marine work force has declined 60 percent since 1970 and is

still dropping. Seventy-six US shipyards or ship repair facilities have closed since 1982, and 38 major dry docking facilities have shut down . . . [making] it harder for the Navy to reactivate reserve ships quickly or to repair battle damage... This is particularly discomforting in light of the fact that 95 percent of dry cargo and 99 percent of petroleum products for an extended overseas deployment will require sealift. (Correll: 40 - 41).

Joint Operations Planning

Various contingency plans and war plans are laid out by operational planners within the Joint Chiefs of Staff (JCS) in conjunction with the staffs of the responsible war fighting commanders-in-chief (CINCs). Each of these plans has requirements for reinforcing men, supplies, and equipment to be delivered to the war zone according to a time line laid out by the staff of the war fighting CINC. This time line is revised by JCS and US Transportation Command (US TRANSCOM) and finally becomes the Time Phase Force Deployment List (TPFDL), which is an annex to the actual war plan (AFSC: 196-197). The TPFDL includes detailed movements of specific combat and support units, including equipment and supplies, and the Required Delivery Date (RDD) associated with each unit. The terminology for integrating transportation resources to move various units and sub-units from a variety of locations to arrive where specified in the TPFDL is called "closure". To plan whether the units can achieve closure by the RDD, JCS uses several large models. The first is the Model for Intertheater Deployment, by Air and Sea (MIDAS) and the other is the Transportation Feasibility Estimator (TFE) (Haile, 1989).

The models are used to establish whether the TPFDL is supportable. Determining supportability depends on many assumptions about initial conditions. These include attrition, threat force size, warning time of an impending attack, use of allied airfields that are not routinely available in peacetime, levels of pre-positioned material, and other war sustaining factors.

MIDAS and TFE are large, mainframe based stochastic models that take tremendous setup and computer processing time to make a single run (Haile, 1989). While adequate for long range planning, the models are inadequate for analyzing alternatives on short notice.

Current Environment

Recent discussions of conventional force reductions in Europe by the state department have raised questions about changing European defense commitments in general, and airlift requirements in particular (Haile, 1989).

Mandated talks for conventional arms control began in Vienna in November 1986. Conventional arms control concepts have been very popular with the general population in Europe, so the European community certainly has incentives for cooperating with conventional reductions. Some of the concepts considered have been to limit the number of stationary forces in Europe and to limit the number of key weapon systems such as tanks, artillery, and armored troop carriers. Since, by some estimates, nearly half the annual

US defense budget goes to defending western Europe, a large economic incentive should exist for the US to participate in the conventional reductions in addition to humanitarian and political reasons (Marshall:78-83). As evidence of the interest in the conventional limitations, recent discussions in the US Congress raised the issue of using conventional arms control negotiations as a vehicle for greater defense burden sharing by NATO allies (Interim Report).

While reducing arms has many merits, pragmatists realize Soviet forces in Europe would be withdrawn overland and could be redeployed in wartime by truck and rail, while US forces across the Atlantic would still need airlift and sealift to deploy. In fact, any serious consideration of withdrawing forces from Europe will increase the need for strategic lift, since there will be more augmentation needed to bolster overseas forces. This further complicates the problems associated with strategic lift.

When analyzing policy alternatives that consider the changing of force levels, it is not satisfactory to take the same length of time to answer inquiries as is acceptable in long range planning and therefor a quicker, more responsive tool is needed.

The Office of Assistant Secretary of Defense for Program Analysis and Evaluation (OASD/PA&E) has developed a simulation model called MINOTAUR. This model is designed to run on a microcomputer and give a quick estimate of strategic lift requirements for a limited set of input

conditions (Sims). This 'deterministic' model treats cargo in a more aggregate manner than MIDAS or TFE and uses heuristic techniques to schedule cargo movements. Minotaur treats airlift as an aggregate daily capacity and uses individual ship entities for modelling sealift (Keyfauver et al, 1988).

Two advantages of this type model are evident. The first advantage is that the model can be run on a standard IBM AT compatible machine by a large number of users. With widely accepted output results, a great deal of insight can be gained on preliminary planning questions with a desktop model. A second advantage is that a deterministic model requires only one run to determine output from a set of inputs. A stochastic model such as TFE requires a statistically large number of runs to create an output value probability distribution. Using MINOTAUR, a single run can give insights into a particular contingency scenario. This feature can be exploited by designing an experiment where input factors of interest can be set at a number of different levels to create a response surface. The response surface can typically be expressed as a polynomial which describes the desired output as a combination of input factors. This can be used for prediction, for insight, or as a way of searching for a better combination of inputs to improve output (Box and Draper: vi-vii).

The MINOTAUR model does have several drawbacks. It does not consider attrition of cargo aircraft or ships. It does

not convoy ships. It also does not generate a requirements schedule for resupply as events change after the beginning of the conflict. It does not read requirements information from any mainframe data base, although other programs do exist for down loading data for this type application (Keyfauver et al, 1988). Before the model could become widely accepted, it would need to be validated. A likely technique is to compare MINOTAUR output against accepted results from empirical data or another approved model. Validation of MINOTAUR is beyond the scope of this thesis. However, MINOTAUR run output data are being compared to MIDAS output data at OASD/PA &E as a form of model validation (Sims).

Another caveat to be considered before using the model to create a response surface is that one needs an accepted model output to use as a basis to judge the effects of the inputs. Several aggregate measures of merit or measures of effectiveness (MOE) are currently popular in the airlift community. These include millions of ton miles per day (MTM/D) of cargo carrying capability, utilization rate of airlift aircraft (Ute rate), and closure time for a specific set of cargo (that time when a complete set of a unit's requirements are delivered to the warfighting user) (Merrill). Both MTM/D and Ute rate are more indirect measures of airlift capability (goods moved) rather than measures of effective airlift (goods moved on time to the right place). Effective military airlift might be described

as the ability to deliver combat power to the user when it is needed. Closure time is a good measure of merit, but is not easy to measure accurately. To do so requires considering the effect of cargo moved to a location near, but not at, the location of the user, constraints on port facilities, manning constraints for the transportation system, attrition, weather delays, etc. The higher resolution models which are capable of this type of detailed analysis (MAC's M-14 model, for instance) require large set up times, long run times, and extensive programming experience to get one run accomplished. They also tend to have programming errors and may not have adequate model validation. For these reasons, models such as MAC's M-14 airlift model are no longer in use (Bauer, Strickland). The slightly more aggregate mainframe models which MAC uses now cannot generate an on-target, on-time cargo criterion. Some MOEs are available, but no one captures the proper capacity, location, and timeliness aspects simultaneously. Mobility planners cling tenaciously to MTM/D (Humley).

To take a single new MOE that does not comprehensively measure airlift effectiveness and convince the airlift community of its worth appears difficult, logically. A potential avenue around this opposition is to take a number of measures that approach being complete and combine them via some sort of weighted averaging to create an effectiveness index for airlift.

Objective

This thesis will develop, using a representative unclassified data set, experimental designs which will be used to screen factors and generate a response surface for the MINOTAUR mobility model. Validation of the metamodel is essential before judging the success of this objective. To do this, a new set of test design points are used to demonstrate the accuracy of the metamodel predictions in relation to the actual model outputs. With a valid metamodel, quick estimates for strategic lift capabilities can be generated using the small set of input parameters which have shown to have large impact on MINOTAUR model output. Sample calculations will be demonstrated.

Sub-objectives. These include developing a new measure of effectiveness for strategic lift which can take the loss of lift assets into account, as well as the associated cargo loss.

The new MOE could be a model output or some sort of new index or weighted average created from model outputs. Success in developing a MOE would be to find an MOE that can be predicted by the metamodel and reflects some parameter of interest for strategic lift.

II. BACKGROUND

This chapter section addresses three general areas: the MINOTAUR model, characteristics of response surfaces, and output data analysis techniques.

The MINOTAUR Model

MINOTAUR came into existence because of the need for a quick estimating tool for strategic lift requirements. The large mainframe models mentioned previously take a great deal of preparation time and computer time to run, making them impractical for quick analysis.

Previous PC compatible models were also inadequate. An existing small model for modeling strategic mobility was Better than the Back of an Envelope (BBOE), an airlift model developed by the OASD/PA&E staff. BBOE lacked the ability to model sealift and was limited to a single theater of operations. Another small linear programming model, OPTAIR, modeled airlift along a single route and minimizes flight time along the route.

A problem with these models is the difficulty in using them for accurately modeling a large number of deploying units over a long period of time using sealift assets which have a widely differing set of capabilities. Both models are too aggregate to readily program all the individual mobility requirements and details of specific requirements are lost in the aggregation (Keyfauver,1986).

MINOTAUR is a discrete event simulation model for strategic airlift and sealift. The model does not use any sort of math programming formulation to model strategic lift, although distances between seaports are computed using an "all shortest paths" algorithm. Strategic airlift is treated as a single large CONUS-to-theater arc. In both cases, flow is not constrained by facilities, maintenance, fuel, etc.

The model uses heuristic rules for scheduling cargo movements. The objective of the scheduling algorithm is to deliver requirements within a specified period or time window before their required delivery date (RDD), preferably in the sequence determined by the RDDs. If this is impossible, it will schedule the requirement as soon as it is able after the RDD. The window is user specified. MINOTAUR does not simulate movement of in place units or prepositioned cargos. These cargos are available at their RDD by definition.

Sealift. Ships move from various seaports to the combat theaters over a maximum of 179 arcs. Individual ships are modeled moving across this "network." Cargos are selected for sealift scheduling in order of their expected on-time-departure date at their assigned port of debarkation (POD). Those requiring the earliest expected departure date are processed first. Ships unable to meet their scheduling window are reserved for future use so that they are not taken up carrying cargos on shorter routes where they could

make schedule. One could say the earlier RDDs have priority. In a sense, late arrivals for near-term RDDs are kept to a minimum rather than maximizing on-time cargos for all RDDs. The model will search all reserved and scheduled ships to find unused capacity and will mix cargos to use all available capacity whenever possible.

MINOTAUR starts by loading containerized cargo on a ship to fill the designated containerized hold area. It next loads non-containerized cargo in its designated area, and when or if this is done, the remaining non-container space is filled with containers until the ship is fully grossed out, either by volume or deadweight.

Airlift. Aircraft are not treated as individual entities. Airlift allocation is computed after available sealift. Sealifted cargo is subtracted from the total required cargo for movement. Container cargo loads are considered equivalent with outsize air cargos when determining the required cargo remaining by type. Requirements are driven by their RDD date for airlift. MINOTAUR uses a single numerical computation with a daily ton-mile capacity calculation for each aircraft (A/C) type as shown in Equation 1 (Keyfauver et al, 1988).

As with ships, a preferred cargo scheduling order exists. Outsize cargos go onto outsize capable aircraft, followed by bulk/oversize cargos going on bulk/oversize limited aircraft. Bulk/oversize is then scheduled for outsize available aircraft, followed by passenger aircraft

carrying passengers. Utilization rate is discussed further in the literature (Gearing and Hill).

$$\text{Daily Ton-mile Capacity} = \text{A/C Number} * \text{Ute Rate} * \text{Speed} * \text{Payload} \quad (1)$$

where

A/C Number	=	number available A/C, by type
Ute Rate	=	daily A/C utilization rate (hr/day)
Speed	=	average speed of the A/C (knots)
Payload	=	total cargo payload (short tons)

To date, no literature has been found on studies done using MINOTAUR. Documentation does exist on the model itself, describing the use and general layout of the model. The model is written in turbo pascal version 4.0 and runs on an IBM AT compatible computer with a 80287 math co-processor and requires 640 k of RAM (Sims).

Response Surface Methodology (RSM)

Within this search of RSM literature are the sub-topics of underlying theory, use of an experimental design, and examples of applications in RSM.

Theory. A response surface model is a mathematical model that represents the behavior of an output, y, as a function of the various inputs, x_i. Typically empirical models use a polynomial to express the input/output relationships, either as raw input variables or as linear transformations of the raw variables. These models are used when the underlying model mechanism is unknown or poorly

understood (Draper,1984:1). Mechanistic models can also be used when a good under-standing of the underlying functional relationships are known. However, these models are harder to fit and are usually non-linear. When little is known about the nature of the model mechanics, empirical techniques can be used to fit a polynomial to the unknown surface by finding estimates of the first order terms in the Taylor series expansion for the unknown function. By choosing a small enough region of interest, a reasonable model can usually be formed by either a first or second order polynomial (Draper,1984: 2).

The Experimental Design Matrix. It is a common practice to "code" the input variable x_i's (the regressors) via the linear transformations in Table 1. By doing so, the regressors become the orthogonal columns which form the design matrix and the input variables are guaranteed to be independent of one another. Later, when the response surface is built, the coefficient estimates will also be independent and will give a correct representation of the weight or influence the inputs have on the output response y (Bauer,1989; Draper,1984:3).

The mappings in Table 1 are a specific example of a more general coding scheme where a location parameter is subtracted off the input data value and the result is divided by some dispersion parameter.

Table 1. Mapping Input Variables from 1 to -1

Raw Data Input	Data Transformation	Coded Data Value
Largest Value	(Input - mean)/((Max - Min) * .5)	1
Mean Value	(Input - mean)/((Max - Min) * .5)	0
Min Value	(Input - mean)/((Max - Min) * .5)	-1

It is, in some sense, a standardizing of the input variable data. The reasons for this type of coding will be more clear after the discussion of experimental design.

After coding the inputs x_{1u}, x_{2u},...,x_{ku}, a least squares regression is set up to form an equation of the form

$$y_u = \beta_0 + \beta_1 * x_{1u} + \beta_2 * x_{2u} + \ldots \beta_k * x_{ku} + \varepsilon \qquad (2)$$

where

- y = Dependent variable
- x = Independent variable(s)
- β = Regression coefficient
- k = Total number of input variables
- u = The total number of experimental design points
- ε = Error

Equation 2 is a first order, or linear, model.

Additional experimental design points might later be added to allow estimation of the coefficients for interactive and/or higher order terms of x_{ku} if the linear model is inadequate. As will be shown, adding regressors require more runs of the model to determine their effects.

The sets of all the regressors x_{1u}, $x_{2u}, \ldots, x_{ku}$, form the experimental design points for the model runs. These may be regarded as an ordered pattern of points in k dimensional space. The response surface design is simply an experimental arrangement of points which permit the fitting of a response surface to the corresponding observations y_u. The order of the experimental design corresponds to the order or degree of the polynomial to be fitted (Draper:3).

The key strength of an experimental design is to allow the user to conduct a minimal number of experimental runs to answer the questions the experiment was created to answer.

By using the variable codings from Table 1, the columns of the design matrix are orthogonal. This provides an experimental design matrix which can be orthogonally blocked so that the effects on results across blocks are independent of one another. Here, the blocking scheme is arranged so that differences between levels of the various blocks do not affect the final estimates. Such a design is termed sequentially blocked (Draper:8). Typical designs are full and fractional factorial designs, central composite designs, Plackett-Burman designs, and small composite designs.

Full factorial designs include all interactions of variables and are the most comprehensive. However, the number of computer runs grows exponentially with the number of input variables and the desired order of the terms in the fitted response function (Kleijnen: 259). The required number of computer runs is based on the levels of the input variables raised to the power of the number of input variables. For example, with two levels (1 and -1 from Table 1 codings), and eight input variables, 2^8 runs are required. This is sometimes called a 2^k design (for k variables).

Fractional designs allow one to create models that have a large number of input variables in a smaller number of runs than full factorial designs by using (either for substitution or for blocking) extra input variables in the columns of the 2^k factorial matrix where the original interaction variables were. The hope is that the original interaction variable might have a negligible effect on model output, and nothing would be lost in making the substitution.

The advantage of fractional designs is either more new effects can be estimated in an equal number of runs (by substituting), or a smaller subset of effects can be estimated in a smaller number of runs (by blocking). The drawback is that the effects of the extra input variable cannot be distinguished from those of the interactive

variable in the event the negligible effect assumption was wrong. This is known as an aliasing or confounding problem.

Sources also exist which demonstrate a fractional experimental design can be generated from a FORTRAN computer program (Turiel:63-72; Franklin:165-172). These require the user specify which effects to estimate beforehand.

Central Composite Designs (CCD) allow the user to run an experiment to create a first order model using a factorial or fractional design and later use the first order data as a building block for a second order model by adding points to, or augmenting, the design matrix.
This is often referred to as a 2k design, with k total additional design points.

Plackett-Burman designs are useful in creating a linear model since all columns in the design matrix are orthogonal (or nearly so) and the number of runs is the same as the number of input variables.

Small composite designs are an augmentation of a Plackett Burman Design to give second order effects when a linear model is inadequate. The advantage of these over central composite designs is the smaller number of runs required to estimate second order effects in the model.

Woven throughout all of these designs is the idea of the resolution of the design. Resolution involves the types of aliasing that exist in the model. If no main effect is aliased with any other main effect, the design is at least Resolution III. If no main effect is aliased with any two-

way interactive effect, the design is at least Resolution IV. If no two way interactions are aliased with each other, it is at least a Resolution V design. Generally more runs are required for a given design to achieve the higher resolution.

Further detailed discussions of experimental designs can be found in several well known texts. Examples by Cochran and Cox and by Hicks are listed in the bibliography.

Examples of RSM-related Applications. The literature contains attempts to create an expert system to allow the user to build a response surface. Sparrow designed a user friendly program to run on a VAX 11/780 computer. This program allowed interactive experimental design and set up a response surface for Fortran-based models. The program focused on factorial and fractional factorial designs but did not include Box-Behnkin techniques (Sparrow). The program works with first and second order models but cannot search the surface for optimality. Unfortunately, the system is not compatible with Pascal based programs such as MINOTAUR, and does not run on a microcomputer.

The literature cites many successful uses of RSM for optimization. A paper from the 1985 MORS conference found

> ... RSM allows math and statistical tools to be used... to examine factor relationships and to determine which combinations of factors result in the optimum output. (Smith and Mellichamp)

A number of works have used RSM successfully in dealing with networks. A recent study used RSM in exploring the

characteristics of binary stochastic reliability networks (Bailey:ii). Several linear programming or math programming models laid out a deterministic network for airlift and created a response surface to capture the essential behavior of the system they described. The use made of RSM here was to aid in gaining insight. Haile built upon a previous goal programming model to design a model to optimize an airlift force structure for a far eastern operations area by using combat power delivered as a measure of effectiveness (Cooke; Tate; Haile, 1986). Haile noted that the optimization problem was highly scenario dependent. The same model was later modified, again using math programming techniques, and included mission and aircraft-specific attrition. The work also included a decision support system to allow flexibility in changing the scenario more easily (Hagar:11).

These examples demonstrate successful application of RSM techniques on the mobility models. However, none of the previous desktop mobility model captured the effects of multiple theater scenarios, sealift, and the resupply problem over a long time horizon. The response surfaces generated from them, while accurate predictors, do not address the complete strategic lift scenario. The experimental design and response surface for MINOTAUR will represent a more complete picture of strategic lift.

A further review of applications of RSM can be found in technical reports cited in the bibliography (Myers and others).

Output Data Analysis

A number of techniques exist for analyzing multivariate output data. These techniques are based on the statistical principals that deal with random variables. Since MINOTAUR is a deterministic model, due caution is necessary both in using these techniques and in developing conclusions or insights based on classic statistical methods. However, by perturbing the output variables by manipulating the independent input variables, pseudo-stochastic changes in the output variables can be observed and the tools can still be applied, albeit in a more limited fashion. The hope here is that analyzing outputs can yield a new MOE for strategic lift.

Two commonly used multivariate techniques are Principle Component Analysis (PCA) and Factor Analysis (FA).

Principal Component Analysis.

PCA is used to reduce the dimensionality of the output variables by examining the covariance or correlation structure of the outputs and providing a small number of new, independent linear combinations of the original outputs which might be easier to interpret than the original, more numerous, outputs. (Bauer). A notional example might be replacing (providing the data bore this out) a person's height, weight, neck size, and trouser inseam length with one (or more) indices which were a linear combination of the original four factors.

The underlying theory for PCA is that if the output variables can be collapsed into a smaller number of indices, it is because some of them are correlated (not independent), and their degree of correlation is reflected in the correlation and covariance structure of the output data. Those original output variables that contribute most to the overall variance of the output data are most heavily weighted in computing the new output index (or indices). The determination of contribution to overall variance is accomplished by setting up a problem to find the linear combination of output variables which maximizes the amount of total variance (Dillon and Goldstein). The weights are constrained so that they cannot exceed one (so that the objective function cannot be made arbitrarily large). This can be seen in Equation 3.

$$\text{Maximize} \quad \underline{\Gamma}^{T} \Sigma \underline{\Gamma} \qquad (3)$$

$$\text{such that} \quad \underline{\Gamma \Gamma}^{T} = 1$$

where Σ = A p x p covariance matrix of the p original output factors

$\underline{\Gamma}$ = The vector of the coefficients for the linear combinations of the p factors.

When Lagrange Multipliers are used to optimize Equation 2, the solution takes the form of Equation 4 below.

$$(\boldsymbol{\Sigma} - L_1 \mathbf{I})\underline{\boldsymbol{\Gamma}}_1 = \underline{0} \qquad (4)$$

where L_1 = The Lagrange Multiplier for the optimization

$\mathbf{I}$ = The p x p Identity Matrix

$\underline{\boldsymbol{\Gamma}}_1$ = The weighted coefficient vector. Also called the first Principal Component

Upon further observation, it can be seen Equation 4 has the same solution set as the Eigenvectors and Eigenvalues for the covariance matrix. The Lagrange multiplier is equivalent with the largest eigenvalue for the covariance matrix, and the first principal component is the eigenvector associated with the largest eigenvalue (Dillon and Goldstein: 27-29). The variance of the first principal component is the largest eigenvalue, as shown by Equation 5.

$$\underline{\boldsymbol{\Gamma}}_1^T \, \boldsymbol{\Sigma} \boldsymbol{\Gamma}_1 = L_1 \qquad (5)$$

It is often useful in interpreting the principal component information to compute a loadings matrix which shows how the original output measures load on the principal components. The loadings matrix is computed as shown in Equation 6.

$$\mathbf{M} = \mathbf{A}_r \, \mathbf{\pounds}^{1/2} \qquad (6)$$

where

$\mathbf{M}$ = The loadings matrix

$\mathbf{A}_r$ = The matrix composed of columns of the normalized eigenvectors of the correlation matrix

$\mathbf{\pounds}$ = The diagonal matrix of eigenvalues from the correlation matrix that satisfy $\Gamma \Gamma^{T} = 1$.

A quantity known as the component score can also be created once the principal components have been determined. The component score is the product of the standardized output data matrix and the appropriate column(s) from the eigenvector matrix. This is shown in Equation 7.

$$\mathbf{Z} = \mathbf{X}_s \, \mathbf{A}_r \qquad (7)$$

where

$\mathbf{Z}$ = The matrix whose columns are the component scores

$\mathbf{X}_s$ = The matrix of standardized output data

$\mathbf{A}_r$ = The matrix composed of columns of significant eigenvectors from the correlation matrix

The first component score is the linear combination of the original output data which accounts for the majority of the variance in that output data. The number of principal

components retained depends on the relative size of the eigenvalues. A ratio can be formed between an individual eigenvalue and the sum of all the eigenvalues. This ratio represents the fraction of the overall variance explained by that single principal component, and gives a valid basis for judging which principal component scores to retain. The idea is to have a minimum number of scores which account for the vast majority of the variance, and use those scores as a new MOE in place of the original data. This can be done with the correlation matrix as well as the covariance matrix, with the advantage that the new MOE is unitless and is not adversely influenced by very large differences in the variances of the original output data. The eigenvalues, eigenvectors, and component scores from covariance data are different than those obtained from correlation data and consistency in the computations is essential.

Factor Analysis

Factor Analysis differs from Principal Component Analysis in that the output variables are said to be manifestations of some unknown (group of) underlying factor(s). Factor analysis is based on the common variation between the variables, while PCA is based on total variation. The total variance can be decomposed into common and unique as shown in Equation (8).

$$\Sigma = U U^T + \varepsilon \tag{8}$$

where

Σ = The p x p covariance matrix of the observable output variable, y

U = The p x q loadings matrix representing the common variance for the unobservable common factors

ε = The p x p matrix of unique variances

The general formulation for factor analysis for p outputs and q factors is expressed by Equation 9.

$$Y = U f + \varepsilon \tag{9}$$

where

Y = A p x 1 matrix of observed responses

U = A p x q matrix of factor loadings

f = A q x 1 matrix of unobservable common factors

ε = A p x 1 matrix of unobservable unique factors

Another difference in the two techniques is that PCA allows a unique solution, while FA allows an infinite number. In FA, the analyst chooses a preferred solution based on some pre-conceived criteria. FA is heavily dependent on assumptions about the dimensionality of the

underlying factors and on the particular solution technique of the user.

Factor analysis relies on the analyst's a priori knowledge of the system in question. The analyst has considerable leeway in arriving at a solution, and thus results are often open to interpretation.

An example where factor analysis might be used is when the outputs variables are gemstone characteristics, such as cut, carat, clarity and color. A FA hypothesis which might be tested is whether the underlying factor space is one dimensional, and whether a single underlying factor (which itself is not directly measurable) can logically tie all the output variables together. A factor such as quality or worth of the stone might do so. It is crucial to note the number of underlying factors and what they represent are postulated by the analyst and are not unique mathematical solutions.

Once a solution is found, it can be transformed by matrix multiplication (a so called rigid rotation) to better accentuate the structure of the loadings matrix. One rotation technique frequently used is varimax, which maximizes the variation of squared factor loadings within a factor (Harman). The FA rotation matrix can also be applied to the Principal Components loadings to help better accentuate them.

III. METHODOLOGY

This effort consisted of screening a database for the experiment, choosing the variables to be candidates for the metamodel, following an overall plan for model building which included an initial experimental design and developing MOEs from available model output data. The general areas of work to attack the problem are described below.

Data Validation

Data for this experiment were obtained from General Research Corporation, the contractor who wrote the MINOTAUR model. The requirements data was roughly equivalent with those of the General Illustrative Scenario used in the defense mobility planning community, although with the requirement dates randomized to prevent any link with real world requirements (Sims). The ship data base was also provided by the contractor, and the 975 ships are representative of the ships available in a major multi-theater conflict. The aircraft database was also provided by the contractor, but modified slightly to keep airlift capacity within the limits of AFP 76 - 2. Airlift data is listed in Appendix D.

A 70 day scenario with 60 days of combat was chosen as a notional scenario length. The length of the scenario, as well as the high and low levels used for the variables, were derived from conversations with mobility planners and

airlift analysts which built upon information in the literature (Ullsamer; Humley; Merrill).

Two theaters, NATO and Southwest Asia (SWA), were played in the scenario to capture multi-theater effects.

Variable Selection

All available input factors were examined for use in the experiment, and then a subset was chosen. Since a very large number of variables could have been candidates for this experiment, some limits had to be placed on the effort. Factors available that were chosen as constants instead of variables were length of conflict, number of and availability of ships, number of theaters of conflict, and number of ports. All of these had a potential to affect model output, but airlift was chosen as the central question of interest. By contrast, had ships been included, varying their numbers (considering their vast cargo capacity) would have totally dominated model output and masked the effect of changes in airlift. Since the aggregation level of MINOTAUR masks much of the flexibility and responsiveness of airlift over sealift, it seemed inappropriate to show sealift as dominant due to its tonnage alone. The list of the 13 variables actually used is shown in Table 1A.

Table 1A. 13 Variables Examined in Developing the Metamodel

Warning Time	C-141 Fleet Size
Marry Up Time	C-5 Fleet Size
Port to Destination Delay	KC-10 Fleet Size
C-141 Utilization	C-17 Fleet Size
C-5 Utilization	NB CRAF Fleet Size
C-17 Utilization	WB CRAF Fleet Size
	WB CRAF Pax Fleet Size

Including aircraft number for 7 types of aircraft and utilization rate for the MAC military aircraft was to capture the effect of airlift capacity. Cargo marry up time, which is the delay at a port of debarkation (POD) to process or assemble cargo, was of interest as a constraint. Delivery time, the amount of time to get cargo from its POD to the user, was a test of the in-theater lift capability. Mobilization warning was of interest since it seemed logical to assume a greater head start on mobilization would have a large effect on the ability of the strategic lift system to respond.

Strategic Planning

In taking model outputs and using them to estimate the parameters (ie, the coefficients) of a metamodel, a general screening strategy was used.

Group Screening.

Similar factors were first grouped together and their levels changed as a group to see if the group played a role in the initial group model. If not, the entire group was dropped from consideration for the next more refined model. Once the group screen was complete, the remaining individual factors were screened to check their contributions. When some individual factors were eliminated, a simple metamodel could emerge, and be validated by checking model outputs against predictions from new test design points. This general sequence is shown in Figure 1 (Bauer,1989: 1.3).

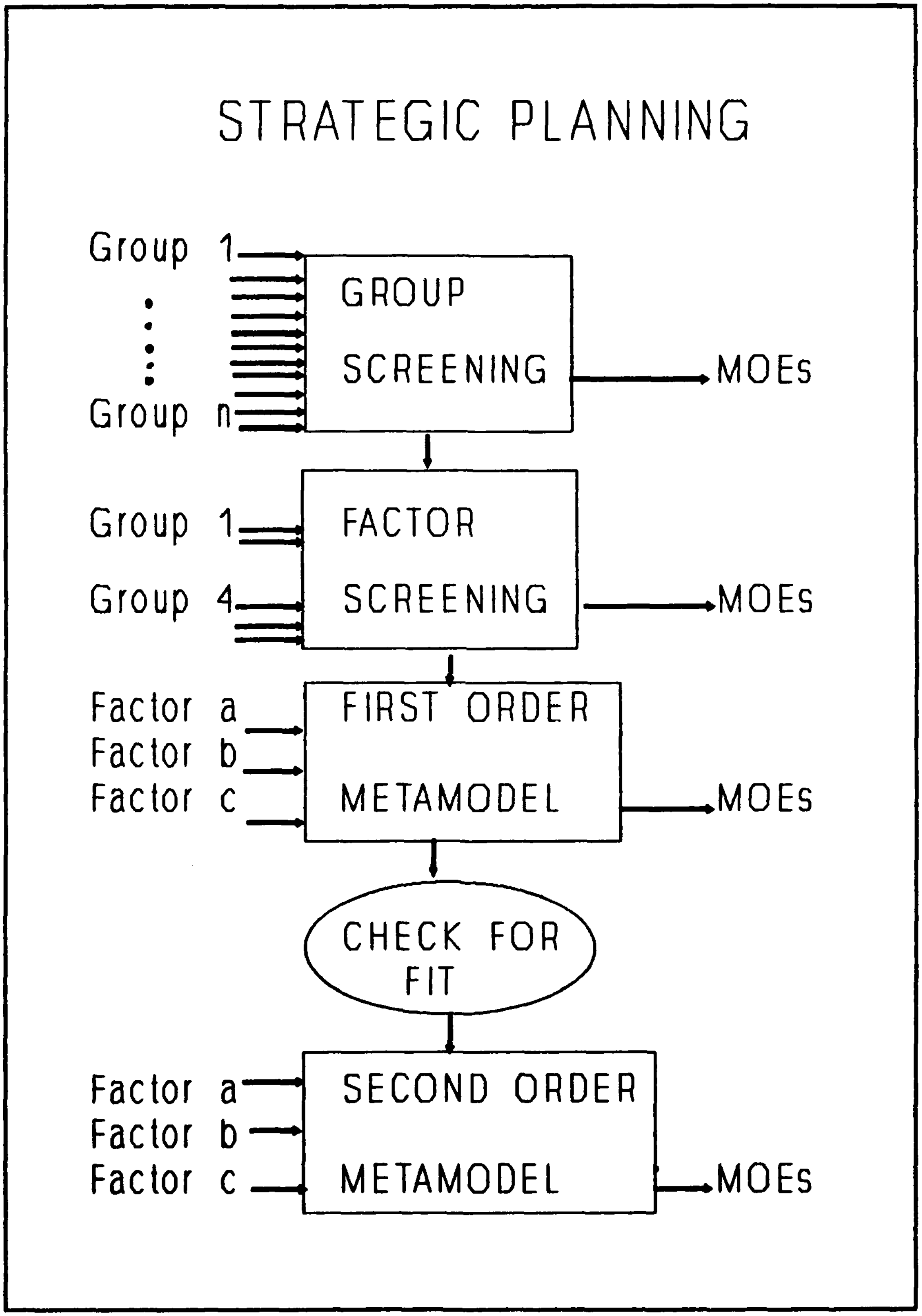

Figure 1. General Overview of RSM Methodology

An initial cut at the group screening problem was to group 13 variables into four simple groups: Number of aircraft, aircraft utilization rate, In-theater delays, and mobilization warning time before war. These groups are shown in Table 2, with high levels being favorable to strategic lift.

Model Formulation. A word of caution is necessary here regarding screening and model selection. Since MINOTAUR is a deterministic model, many of the traditional statistical tests are invalid, such as the acceptance or rejection of a hypothesis test with a central F statistic. The primary criterion used to judge model adequacy was adjusted R^2, or how well the model fit the data considering the number of degrees of freedom. It is computed as shown in Equation 10.

$$\text{Adjusted } R^2 = 1 - ((n - 1) * (1-(SSR/SST))/(n-p-1)) \quad (10)$$

where

n	=	Number of runs
p	=	Number of Regressors
SSR	=	Residual Sum of Squares
SST	=	Total Sum of Squares

Table 2. Group Screening Variable Values

Group 1 Aircraft Number	High / Low Levels of Variable
C-141	234 / 160
C-5	110 / 85
C-17	210 / 150
KC-10	60 / 20
Widebody CRAF Cargo	150 / 100
Narrowbody CRAF Cargo	120 / 50
Widebody CRAF Passenger	340 / 380
Group 2 Aircraft Utilization Rate (Flying Hours per Day) (30 Day Surge)	
C-17	15.2 / 13.9
C-141	12.5 / 10.0
C-5	11.0 / 9.0
All Others	10.0 / 10.0
Group 3 In-Theater Delays (Days)	
Cargo Marry Up Time	0 / 1
Port to User Delay	1 / 2
Group 4 Mobilization Warning Time Before War (Days)	
Warning Time	10 / 5

Assumptions :

30 Day Surge in Military Cargo Utilization Rate

50 % All Aircraft Available Day 0
80 % All Aircraft Available Day 1
95 % All Aircraft Available Day 2
100% All Aircraft Available Day 3 and Beyond

A secondary indicator in screening and model selection is Mallow's C_p statistic. This statistic is useful because it indicates that not including an important variable in the model could bias the fitted coefficients. A proper model would have a C_p nearly equal to (but not less than) the number of factors in the model (Weisberg).

A third indicator used as a loose guide in factor selection is the relative standings of the factors in relation to the F-test associated p-value in the analysis of variance information. Although not a statistically valid acceptance test, a variable with a very large p-value compared to other factors would lead one to think hard before including that factor in a model.

Finally, graphical plots of model fit vs standard residuals and normality plots of standard residuals should help accentuate any trends in the residuals, such as an indication of quadratic form in a first order model or a residual dependency on the size of the predicted output values.

Experimental Design

It was uncertain whether the inputs would generate a first order response surface, but the simple, non-constrained nature of the strategic flow in the model gave no outward indication a higher order process would exist. Therefor, a Plackett-Burman design was chosen for the group factor screening, since a design requiring only 8 runs could

give an estimate for four factors (the four groups in the group screen) with no aliasing among main factors if a linear process existed. Actually, fewer runs were required for 4 factors but gaining additional degrees of freedom seemed worth the effort. The input levels for the factors are shown in Table 3.

Table 3. Plackett-Burman Design Inputs

GROUP 1. Aircraft Number

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run8
C-141	234	160	160	234	160	234	234	160
C-5	110	85	85	110	85	110	110	85
C-17	210	150	150	210	150	210	210	150
KC-10	60	20	20	60	20	60	60	20
WB Cargo	150	100	100	150	100	150	150	100
NB Cargo	120	50	50	120	50	120	120	50
CRAF Pax	340	280	280	340	280	340	340	280

Group 2. Aircraft Utilization (Hours/Day)

C-141	12.5	12.5	10	10	12.5	10	12.5	10
C-5	11	11	9	9	11	9	11	9
C-17	15.2	15.2	13.9	13.9	15.2	13.9	15.2	13.9
KC-10	10	10	10	10	10	10	10	10
WB Cargo	10	10	10	10	10	10	10	10
NB Cargo	10	10	10	10	10	10	10	10
CRAF Pax	10	10	10	10	10	10	10	10

Group 3. In-Theater Delays (Days)

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Marry Up Time	1	0	0	0	1	1	0	1
Port to Destination Time	2	1	1	1	2	2	1	2

Group 4.
Warning Time Before Mobilization (Days)

Warning Time	5	5	5	10	10	5	10	10

Measure of Effectiveness

The MINOTAUR output reports are available in several different formats: tables, reports, summary reports, graphs, and a statistical summary. The statistical summary seemed particularly useful since the type of long range planning referenced in Chapter I depends most on aggregate measures of effectiveness and not the date unit x arrived in location y.

The MINOTAUR Run Report, as it is titled, has tonnage breakdowns by theater, cargo type, and delivery mode. It shows tons delivered on time and those delivered a specified number of days late. A representative sample of a run report is shown in Appendix G. From the available outputs, several potential MOEs were examined. The first was On Time Tons, which is defined in Equation 11.

$$\text{On Time Tons} = \sum_{i=1}^{\text{All Theaters}} (1 - (\%\ \text{Late Cargo} / 100)) \times (\text{Tons Delivered}) \quad (11)$$

Another measure of the timeliness of cargo delivery is to measure how long after the Required Delivery Date the late cargo cargo arrives. A statistic can be formed by summing the product of late tons and average days late over all cargo types and all theaters. The formulation is shown in Equation 12.

Late Ton Days =

$$\sum_{i=1}^{\text{All Theaters}} \sum_{j=1}^{\text{All Cargo Types}} (\text{Tons Delivered}) \times (\%\ \text{Late}) \times (\text{Avg Days Late}) \quad (12)$$

A third measure of airlift that can be extracted is the simple measure of air tons moved. This is the percent total tons moved by air across all theaters. This calculation is shown in Equation 13.

Air Tons Moved =

$$\sum_{i=1}^{\text{All Theaters}} (\%\ \text{Moved By Air}) \times (\text{Total Tons Delivered}) \quad (13)$$

Another measure which could accentuate any cargos that arrive delinquent (by defining anything arriving more than a set number of days after RDD as delinquent) is available by setting a lateness parameter at the time the Run Report is produced. The lateness parameter is the number of days late to use as a delinquent threshold. The MOE can be found by summing the percentage of the Lateness Variable times the delivered tons and summing over all cargo types and theaters. Delinquent Tons is defined by Equation 14.

Delinquent Tons =

$$\sum_{i=1}^{\text{All Theaters}} \sum_{j=1}^{\text{All Cargo Types}} (\text{Tons Delivered}) \times (\%\ \text{More than 3 days Late}) \quad (14)$$

Since the first MOE, On Time Tons, reflects timeliness and tonnage, and is simple to understand, it might be the MOE of choice in forming the response surface from the input variables listed earlier. However, to test whether the aggregate On Times Tons statistic is masking some important features of the individual cargos, On Time Tons statistic will be gathered for selected cargos, by theater, as well. The output variables can be subjected to a Principal Components analysis to assess the true dimensionality of the output data. Principal Component scores from the data could also be used as a MOE in its own right if they explain the pseudo-variance in the data sufficiently.

To help assess the dimensionality of the data, additional runs were completed outside the experimental design by varying numbers of ships and number of aircraft at seven different levels and examining the variance structure. This additional data also allowed Factor Analysis to be performed to give insight on the dynamics of the underlying processes in the model.

IV. EXPERIMENTAL PROCEDURE

As described previously, the first step in the metamodel process was to execute the eight group screening design. The results are shown in Tables 4A and 4B. The model fit was good with Groups 1 and 4 explaining most of the fit of the model. Groups 2 and 3 contributed little to the fit using On Time Tons as an MOE (Table 4A), and even less using Air Tons Moved as an MOE (Table 4B). The small contribution in Adjusted R^2 from Groups 2 and 3 was the primary criterion for dropping them from further consideration.

Table 4A. Group Screening Regression of On Time Tons

LEAST SQUARES LINEAR REGRESSION OF ON TIME TONS

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	4.1982E+06	7805.9	537.83	0.0000	
A/C NO.	6.7181E+04	7805.9	8.61	0.0033	.5894
UTE RATE	2.3615E+04	7805.9	3.03	0.0565	.6194
DELAYS	-2.1202E+04	7805.9	-2.72	0.0728	.6373
WARNING	3.5507E+04	7805.9	4.55	0.0199	.9388

CASES INCLUDED	8	MISSING CASES	0
DEGREES OF FREEDOM	3		
OVERALL F	27.82	P VALUE	0.0105
ADJUSTED R SQUARED	0.9388		
R SQUARED	0.9738		
RESID. MEAN SQUARE	4.875E+08		

After Groups 1 and 4 passed the group screen, 8 individual factors remained. One of these, the widebody passenger aircraft, appeared unlikely to contribute to the cargo related MOEs (since it carried only passengers, only cargo). However, it was kept in as a predictor. Any factor contributing the same amount (or less) than the passenger jet would not be appropriate to keep in the model.

Table 4B. Group Screening Regression of Air Tons Moved

LEAST SQUARES LINEAR REGRESSION OF AIR TONS MOVED

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	6.1936E+05	3107.7	199.30	0.0000	
A/C NO.	.4508E+05	3107.7	46.68	0.0000	.9536
UTE RATE	1.6827E+04	3107.7	5.41	0.0124	.9625
DELAYS	-1.6214E+04	3107.7	-5.22	0.0137	.9741
WARNING	1.7204E+04	3107.7	5.54	0.0116	.9969

CASES INCLUDED	8	MISSING CASES	0
DEGREES OF FREEDOM	3		
OVERALL F	566.6	P VALUE	0.0001
ADJUSTED R SQUARED	0.9969		
R SQUARED	0.9987		
RESID. MEAN SQUARE	7.726E+07		

The next step was to select a design for the factor screening. After group screening showed a good fit with a linear model, it seemed appropriate to set up a design for factor screening which did not require design points which tested for higher order terms. A 2^4 factorial base matrix, requiring 16 runs, was saturated in four of its columns to become a 2^{8-4} fractional matrix. The 4-way interaction and

all but one of the 3-way interactions were used to estimate main effects. This seemed a safe assumption since the good fit of the linear terms (Adjusted R^2 form .93 to .99) in the group screen showed no evidence of interaction. The 2^{8-4} design still allowed for estimation of any two-way effects, should they exist. The extra variables were placed into the design matrix in the columns of the 3 and 4-way interactions. At first glance, these new variables looked to have a lower potential to contribute to the model. These were the the Widebody passenger aircraft, since it doesn't haul cargo, and the C-5, KC-10, and Narrowbody CRAF aircraft simply because of the smaller numbers of these aircraft. The levels of the variables are shown in Table 5.

Table 5A. Factor Screening Variable Levels for 2^{8-4} Fractional Design

FACTOR	RUN 1	2	3	4	5	6	7	8
C-17	150	210	150	210	150	210	150	210
C-141	160	160	234	234	160	160	234	234
C-5	110	85	85	110	85	110	110	85
KC-10	20	60	60	20	20	60	60	20
WB CRAF	100	100	100	100	150	150	150	150
NB CRAF	50	120	50	120	120	50	120	50
WB PAX	280	280	340	340	340	340	280	280
WARNING TIME	5	5	5	5	5	5	5	5

FACTOR	RUN 9	10	11	12	13	14	15	16
C-17	150	210	150	210	150	210	150	210
C-141	160	160	234	234	160	160	234	234
C-5	85	110	110	85	110	85	85	110
KC-10	60	20	20	60	60	20	20	60
WB CRAF	100	100	100	100	150	150	150	150
NB CRAF	120	50	120	50	50	120	50	120
WB PAX	340	340	280	280	280	280	340	340
WARNING TIME	10	10	10	10	10	10	10	10

The results of the factor screening runs seemed quite promising at first glance. Using all four MOEs, model fit appeared good with all Adjusted-R^2 values above .88 as shown in Table 6 (An anomaly with using four MOEs is that four different models emerged). Unfortunately, the standardized residuals indicated a quadratic form might exist for On Time Tons, Late Ton Days, and Delinquent Tons models (See Appendix B).

Three validation runs were performed as a first cut at testing fit. When the three validation data points were checked against metamodel predictions, two of the MOEs fit reasonably well, and the other two were very poor, as shown in Table 7.

The data did not seem to indicate a need for a transformation. The range between max and min for the output variables was small and plots of the residuals did not show an indication of their size changing as a function of the size of the output variable. However, in an attempt to improve fit, transformations of each of the MOEs were made, using the square and the natural log of the MOE as quick guesses at an appropriate transformation. They provided little or no additional model fit, and were not pursued further.

Table 6. Retained Factors from Factor Screening Runs (Four Measures of Effectiveness)

	Based on Factor Screen (Four Measures of Effectiveness)			
	On Time Tons	Late Ton Days	Air Tons Moved	Delinquent Tons
RETAINED FACTORS		C-17	C-17	C-17
	C-141	C-141	C-141	C-141
			C-5	C-5
			KC-10	
	WB CRAF	WB CRAF	WB CRAF	WB CRAF
			NB CRAF	NB CRAF
	WARNING TIME	WARNING TIME		WARNING TIME
Model Adjusted R-Squared	0.8837	0.9666	0.9532	0.9606

Table 7. Percentage Error in Factor Screening Lack of Fit Test

Differences Between Actual and Predicted
Minotaur Factor Screening Output
(Percent)

	Low Run	Medium Run	High Run
On Time Tons	-9.46	-5.92	10.51
Late Ton Days	72.50	83.38	72.86
Air Tons Moved	-3.07	1.35	0.02
Delinquent Tons	-15.97	51.12	60.95

Because of the lack of fit of the test points and the indication of a quadratic form in the standardized residual plot (see Appendix B), a second order design was necessary.

A small composite design was chosen from recent literature (Draper, 1985: 177-179). This design is 7 columns from a Plackett-Burman 28 factor design which had been augmented with 2 star points for each of the 7 input variables, and one center point, for a total of 43 runs (actually, since this is a deterministic model, and runs 7 and 8 had identical design points, only 42 runs were actually accomplished). The range for the C-5 and Warning Time were varied slightly from previous runs (84-110 vs 85-110 aircraft and 6-10 vs 5-10 days, respectively) since runs were required with these integer variables exactly at their mean levels. The levels of the factors for the second order model are shown in Table 8.

Table 8. Variable levels for the Second Order Model

	Run Number										
	1	2	3	4	5	6	7	8	9	10	11
C-141	234	234	160	160	160	160	234	234	234	160	160
C-5	84	110	110	84	84	84	110	110	110	110	84
C-17	210	150	210	150	150	150	210	210	210	150	210
KC-10	60	60	60	60	60	20	20	20	20	20	60
WB CRAF	150	150	150	100	150	150	100	100	100	100	100
NB CRAF	120	120	120	120	50	120	50	50	50	120	50
WARNING	4	4	4	10	10	10	10	10	4	4	10
	12	13	14	15	16	17	18	19	20	21	22
C-141	234	160	234	160	160	234	160	234	160	234	234
C-5	84	84	84	110	84	84	110	110	110	84	84
C-17	150	210	150	150	210	150	150	150	210	210	210
KC-10	20	20	20	60	20	60	20	60	60	20	60
WB CRAF	150	150	100	100	100	100	150	100	150	150	150
NB CRAF	50	50	120	50	120	50	50	120	50	120	50
WARNING	4	4	10	4	4	4	10	10	10	4	10
	23	24	25	26	27	28	29	30	31	32	33
C-141	234	160	234	234	160	160	234	160	197	197	197
C-5	110	110	84	110	110	84	97	97	110	84	97
C-17	150	210	210	150	210	150	180	180	180	180	210
KC-10	20	60	60	60	20	20	40	40	40	40	40
WB CRAF	150	100	100	150	150	100	125	125	125	125	125
NB CRAF	120	120	120	50	120	50	85	85	85	85	85
WARNING	10	4	10	4	10	4	7	7	7	7	7
	34	35	36	37	38	39	40	41	42	43	
C-141	197	197	197	197	197	197	197	197	197	197	
C-5	97	97	97	97	97	97	97	97	97	97	
C-17	150	180	180	180	180	180	180	180	180	180	
KC-10	40	60	20	40	40	40	40	40	40	40	
WB CRAF	125	125	125	150	100	125	125	125	125	125	
NB CRAF	85	85	85	85	85	120	50	85	85	85	
WARNING	7	7	7	7	7	7	7	10	4	7	

When the new data was regressed, new regression coefficients were formed (The Regression Tables are in Appendix C). The retained variables are shown below in Table 9. Note Air Tons Moved retained only linear regressors while the other MOEs used the second order variables as well (primarily Warning Time^2).

Table 9. Retained Factors Based on Second Order Model

	MOEs			
	On Time Tons	Late Ton Days	Air Tons Moved	Delinquent Tons
RETAINED FACTORS	C-141	C-141	C-141	C-141
	C-5		C-5	
		C-5^2		
	C-17	C-17	C-17	C-17
	KC-10		KC-10	
	WB CRAF	WB CRAF	WB CRAF	WB CRAF
	NB CRAF	NB CRAF	NB CRAF	NB CRAF
	WARNING TIME	WARNING TIME	WARNING TIME	WARNING TIME
	WARNING TIME^2	WARNING TIME^2		WARNING TIME^2
Model Adj-R^2	0.9227	0.9344	0.9959	0.8377

Equations 15, 16, 17, and 18, reflect the uncoded variable coefficients (those coefficients for the actual number of aircraft and warning days) obtained from the small composite design.

$$\text{On Time Tons} = 3161800 + 678.76\ \text{C-141} + 1502.0\ \text{C-5} + 1234.5\ \text{C-17} + 1340.3\ \text{KC-10} + 1340.3\ \text{WB CRAF} + 675.43\ \text{NB CRAF} + 79905\ \text{WARNING TIME} - 2466.1\ \text{WARNING TIME}^2 \tag{15}$$

$$\text{Late Ton Days} = 387500 - 1271.8\ \text{C-141} - 1000.8\ \text{C-17} - 1445.2\ \text{WB CRAF} - 854.87\ \text{NB CRAF} - 664990\ \text{WARNING TIME} + 39510\ \text{WARNING TIME}^2 + 3.9401\ \text{C-5}^2 \tag{16}$$

$$\text{Air Tons Moved} = -179725 + 759.84\ \text{C-141} + 2010.5\ \text{C-5} + 1737.0\ \text{C-17} + 1532.6\ \text{KC-10} + 2081.5\ \text{WB CRAF} + 940.14\ \text{NB CRAF} + 10399\ \text{WARNING TIME} \tag{17}$$

$$\text{Delinquent Tons} = 700480 - 315.70\ \text{C-141} - 255.84\ \text{C-17} - 380.31\ \text{WB CRAF} - 266.89\ \text{NB CRAF} - 96596\ \text{WARNING TIME} + 5931.8\ \text{WARNING TIME}^2 \tag{18}$$

It was now necessary to validate the metamodel equation predicted values with additional simulation outputs to check for accuracy. Nine validation points, with coded values between 1 and -1, were used to check fit (See Table in Appendix C for validation design points). The results are shown in Table 10.

Table 10. Percent (%) Differences Between Actual and Predicted Minotaur Output for Second Order Metamodel Validation

MOE	Validation Run Number		
	1	2	3
On Time Tons	0.27	0.86	-0.77
Late Ton Days	-0.92	11.09	2.37
Air Tons Moved	0.03	6.45	7.19
Delinquent Tons	3.89	-2.92	0.01
	4	5	6
On Time Tons	0.94	0.97	0.96
Late Ton Days	-5.28	4.71	0.02
Air Tons Moved	-0.26	0.05	-0.05
Delinquent Tons	0.80	4.53	6.06
	7	8	9
On Time Tons	-1.07	-0.82	-0.85
Late Ton Days	29.10	-6.63	12.40
Air Tons Moved	0.03	-0.07	0.38
Delinquent Tons	-5.21	-16.48	-9.75

Fit was satisfactory (virtually all errors were less than 10 percent) for On Time Tons, Air Tons Moved, and Delinquent Tons. Late Ton Days did not fit as well, perhaps because it is composed of more individual statistics than than the other MOEs. Three of the four metamodels can be considered valid.

IV. Multivariate Data Analysis

Since multiple measures of effectiveness were available from MINOTAUR, it seemed possible that some of them were redundant, or that the true dimensionality of the output data was considerably less than the number of available MOEs. An investigation of this idea, using Principal Component Analysis (PCA), was accomplished for the data from the response surface design runs, which had varied the levels of two classes of variables: the number of aircraft, by type, and the warning time before the breakout of war.

As a comparison, a second investigation was done for a different data set which varied the number of aircraft as a group and the number of ships as a group. After Principal Component Analysis was complete, Factor Analysis (FA) was done on both data sets to try to interpret, confirm, and compare the dimensionality assessments.

Response Surface Data Set.

To to test whether there might be a way to capture the essence of all four of the MOEs in a smaller number of variables, PCA was run on the output data from the second order small composite design to make a dimensionality estimate.

Because of the differing units of the output variables and their large numerical values, correlation data was used rather than covariance data. The principal components, the

correlation structure, and the loadings matrix are shown in Tables 11 and 12.

Table 11. Correlation and Principal Component Data for Second Order Model (from 4 MOEs)

CORRELATION MATRIX

On Time Tons	1.0000	-0.8154	0.6804	-0.7388
Late Ton Days	-0.8154	1.0000	-0.4058	0.9494
Air Tons Moved	0.6804	-0.4058	1.0000	-0.5104
Delinquent Tons	-0.7388	0.9494	-0.5104	1.0000

	EIGENVALUES	PERCENT OF VARIANCE	CUMULATIVE PERCENT OF VARIANCE
1	3.078E+00	76.9	76.9
2	6.925E-01	17.3	94.3
3	2.161E-01	5.4	99.7
4	1.346E-02	0.3	100.0

Principal Components (Eigenvectors)

FACTOR	1	2	3	4
On Time Tons	-0.5276	-0.1367	-0.7724	0.3260
Late Ton Days	0.5275	-0.4437	0.0239	0.7241
Air Tons Moved	-0.4055	-0.8236	0.3298	-0.2201
Delinquent Tons	0.5282	-0.3257	-0.5422	-0.5665

Table 12. Loadings Matrix for Second Order Model.

MOE		PC 1	PC 2	PC 3	PC 4
1	On Time Tons	-0.521	-0.064	-0.202	0.021
2	Late Ton Days	0.520	-0.208	0.006	0.047
3	Air Tons Moved	-0.400	-0.385	0.086	-0.014
4	Delinquent Tons	0.521	-0.152	-0.142	-0.037

The first principal component weighted the 'timeliness' MOEs (ie, 1, 2, and 4) more so than it weighted MOE 3. This assessment was made after seeing the higher values for MOEs 1, 2, and 4 in the first column of the loadings matrix and in the first column of the matrix of eigenvectors. Note MOEs 1, 2, and 4 are also more highly correlated in the correlation matrix.

The second component weighted the activity level of the airlift system (MOE 3) more. This assessment came from MOE 3's higher loading in the second column of the loadings matrix and its high value in the eigenvector matrix.

If one were to try to condense the output variables into a single metric, Principal Component 1 would likely be adequate. This assessment takes into account the percent variance explained (~ 77%) and the heuristic of retaining only those principal components with eigenvalues greater than one (Kaiser, 1958: 187-200).

One can compute the principal component score for the first Principal Component and use it as a representative MOE for the model. This MOE would be a dimensionless quantity which could be linearly scaled to some index value, not unlike the Dow Jones Industrial Average. Changes in the strategic lift system could be compared, based on their effect on the lift index. Of course, such a component score had to be validated with test data before being used. To do this required a predicted fit from least squares and an actual fit from model output. Unfortunately, there are

several problems associated with this validation. The first problem is that the "actual fit" principal component score is itself a computation. The computation is made using standardized data (requiring an estimate of the mean and variance) and the loadings matrix (which is computed from the sample covariance matrix). The error is additive from all these calculations, and may be unacceptably high. Another, bigger, potential problem is whether the small sample of test data (9 runs) has a mean and variance structure equal to the larger data set. If it does not, then subtracting off the mean and dividing by the standard deviation to make the PC score computation is doomed to failure. Despite these challenges, an attempt was made to validate the Principal Component 1 scores using standardized data.

First, the principal component scores were computed as shown previously in Equation 6. Next, the regression coefficients for the scores were estimated by least squares regression as shown in Equation 19.

$$\hat{\beta} = (X^T X)^{-1} X^T Z \qquad (19)$$

where

$\hat{\beta}$ = The r x n regression coefficient matrix

X = The n x p design matrix with orthogonal columns

Z = The n x r principal component score matrix computed from n design runs

p = The number of regressors

n = The number of runs

r = The number of principal scores retained (probably 1)

Predicted component scores were then found by performing the multiplication in Equation 20.

$$\hat{Z} = \hat{\beta}^T X_v \qquad (20)$$

where

$\hat{Z}$ = The matrix of predicted scores

$\hat{\beta}$ = The regression coefficient matrix

X_v = The validation design matrix

Next, validation component scores were computed from the 9 validation test runs. The results of this test were disappointing, with consistently large errors between the

individual z_i and $\hat{z}_i$ values. They are shown in Table 13 below.

Table 13. Validation Test of Predicted Principal Component Score (Standardized Data)

	Validation Run Number		
	1	2	3
Percent Error in Score	-18.47	633.68	-17.29
	4	5	6
	5024.08	-56.80	30.94
	7	8	9
	-953.13	-516.51	-513.51

An explanation for this poor fit is straight forward. First, as mentioned before, all these estimates contain error, and the combined errors grow quickly. Second, since the validation test data were a small sample compared to the experimental design, the mean and variance were different and biased the PC score computation. As a matter of interest, the scores were recomputed using the 9 run sample mean and variance, recomputed using the larger group mean and the sample variance, and every permutation thereof. None worked any better than those in Table 13. As a lesson learned, before trying to validate the principal component scores, the validation data and the design data should be checked for equal means and variances. If this check fails

there is probably no reason to go further with standardized data.

However, another avenue existed to find a single aggregate MOE and validate it. Since by definition, the first principal component is the vector of weights that would give a linear combination of the output variables that explains the largest amount of variance, it seemed logical to test actual versus predicted values of that linear combination, and use that linear combination as a conglomerate MOE. This aggregate MOE might be dubbed the Strategic Lift Index (SLI). The predicted weighted output variable scores were computed against the actual weighted combinations and the results are shown in Table 14. All 9 runs show acceptable fit.

Table 14. Testing of the SLI MOE, created by a Linear Combination of Output Variables.

Validation Run	Actual Model SLI	RSM Predicted SLI	Percent Difference
1	2016333	2197332	-8.98
2	2258548	2332087	-3.26
3	2436806	2402099	1.42
4	2064669	2176832	-5.43
5	2287966	2259269	1.25
6	2204730	2224161	-0.88
7	2462373	2439360	0.93
8	2553555	2521803	1.24
9	2523485	2486695	1.46

In summary, PCA was performed on the second order model data. It appeared that the 4 aggregate MOEs from the

experiment had a true dimensionality of one. The dot product of the first principal component and the 4 MOEs used previously created the Strategic Lift Index, which performed acceptably for 9 test validation cases.

<u>Aircraft / Ship Data Set.</u>

This investigation explored whether varying the number of ships and aircraft in MINOTAUR would give output responses with equal or different dimensionality than that of the RSM data set. Again, PCA was used to look at the output dimensionality. FA was used for verification and insight.

The inputs used were 7 levels of ships and aircraft which spanned roughly ± 15 percent from the mean values from the RSM inputs. A "block" of 50 representative ships with a variety of characteristics were used to augment or decrease the 975 ship fleet. The numbers are shown in Table 15.

Table 15. Levels of Aircraft and Ships for Output Analysis (Level 7 and 1 are roughly ± 15 % of Level 4)

Level	Ships	C-141	C-5	C-17	KC-10	WB CRAF	NB CRAF
1	825	160	86	150	18	100	50
2	875	172	90	160	25	108	61
3	925	184	94	170	32	116	72
4	975	196	98	180	39	124	83
5	1025	208	102	190	46	132	94
6	1075	220	106	200	53	140	105
7	1125	232	110	210	60	148	116

Note: Levels 1 to 7 correspond to -3 to +3 for A/C in Figure 2. The change in nomenclature is to help distinguish A/C levels from Ship levels on that figure.

In addition to the 4 aggregate outputs used previously, other less aggregate statistics were available. MINOTAUR generates statistics on 12 cargo types for the two theaters (NATO and SW Asia) played in the simulation. An on time statistic for each of six representative types of cargo were extracted per theater (for 12 new MOEs).

These, in addition to the four aggregate measures used in RSM, came to a total of 16 output variables. The question was whether the dimensionality here was similar to that in the RSM multivariate analysis.

PCA was run on 12 of the 16 output variables. The results are shown in Tables 16 , 17, and 18 (See note in Table 16).

Table 16. Aircraft / Ship Data Correlation Matrix

	Z1	Z2	Z3	Z4	Z6	Z7
Z1	1.0000					
Z2	-0.9735	1.0000				
Z3	0.2445	-0.2647	1.0000			
Z4	-0.9452	0.9532	-0.4078	1.0000		
Z6	0.1188	-0.1259	0.4797	-0.1603	1.0000	
Z7	0.9390	-0.9179	0.1519	-0.8818	-0.0997	1.0000
Z8	0.9252	-0.9178	0.1408	-0.8736	-0.1687	0.9892
Z9	0.7285	-0.7506	0.1484	-0.7543	-0.4183	0.8297
Z11	0.3183	-0.3394	0.7996	-0.4232	0.4300	0.2292
Z12	0.2396	-0.1651	-0.0562	-0.2391	-0.1165	0.2236
Z13	0.1962	-0.1714	-0.0215	-0.1839	0.0326	0.1400
Z14	0.1973	-0.1953	0.8689	-0.3241	0.3819	0.1348

	Z8	Z9	Z11	Z12	Z13	Z14
Z8	1.0000					
Z9	0.8663	1.0000				
Z11	0.2303	0.2149	1.0000			
Z12	0.2090	0.0857	-0.2437	1.0000		
Z13	0.1473	0.0279	-0.1292	0.5851	1.0000	
Z14	0.1234	0.0557	0.6625	0.1463	0.0558	1.0000

where

Z1 = ON TIME TONS (TOTAL)
Z2 = LATE TON DAYS (TOTAL)
Z3 = AIR TONS MOVED (TOTAL)
Z4 = DELINQUENT TONS (TOTAL)
Z5 = SOUTHWEST ASIA ON TIME TONS (SWT), ARMOR
Z6 = SWT, INFANTRY
Z7 = SWT, COMBAT SUPPORT
Z8 = SWT, COMBAT SERVICES SUPPORT
Z9 = SWT, RESUPPLY
Z10 = SWT, AMMUNITION
Z11 = NATO ON TIME TONS (NT), ARMOR
Z12 = NT, INFANTRY
Z13 = NT, COMBAT SUPPORT
Z14 = NT, COMBAT SERVICES SUPPORT
Z15 = NT, RESUPPLY
Z16 = NT, AMMUNITION

Note: Z5, Z10, Z15, Z16 were dropped since their change over the runs was less than one percent, and including them would bias the analysis.

Table 17. Loadings Matrix for Aircraft / Ship Data Set (First 6 Principal Components)

	Loading on Principal Component :					
MOE	1	2	3	4	5	6
ON TIME	-0.371	0.041	0.005	-0.081	0.021	-0.004
LATE TON	0.370	-0.032	0.016	0.083	-0.001	-0.010
AIR TON	-0.157	-0.326	0.024	0.094	-0.011	0.036
DELQ TON	0.375	0.012	-0.011	0.041	-0.016	0.005
SWA						
INFANTRY	-0.024	-0.273	0.077	-0.254	0.034	0.007
CBT SPT	-0.364	0.096	-0.031	-0.015	0.022	0.015
CBT SVC SPT	-0.364	0.106	-0.039	0.008	0.003	0.013
RESUPPLY	-0.315	0.122	-0.105	0.120	-0.045	0.002
NATO						
ARMOR	-0.173	-0.296	-0.070	0.043	-0.082	-0.130
INFANTRY	-0.090	0.107	0.316	0.077	0.133	-0.076
CBT SPT	-0.074	0.072	0.321	-0.016	-0.187	0.025
CBT SVC SPT	-0.137	-0.297	0.094	0.141	0.057	0.074

Table 18. Principal Component Data for Aircraft / Ships

PRINCIPAL COMPONENTS BASED ON CORRELATION MATRIX

PC NO.	EIGENVALUES	PERCENT OF VARIANCE	CUMULATIVE PERCENT OF VARIANCE
1	5.807	48.4	48.4
2	2.753	22.9	71.3
3	1.587	13.2	84.6
4	8.784E-01	7.3	91.9
5	4.495E-01	3.7	95.6
6	2.070E-01	1.7	97.3
7	1.548E-01	1.3	98.6
8	6.986E-02	0.6	99.2
9	4.470E-02	0.4	99.6
10	2.479E-02	0.2	99.8
11	1.982E-02	0.2	100.0
12	4.647E-03	0.0	100.0

The dimensionality appears to be three for this data. This is considering the number of Eigenvalues greater than one, and accepting 85 percent of the variance explained as being adequate.

Factor Analysis was also conducted and the results are summarized in Tables 19 and 20. The data was analyzed both with principal factor and principal component extractions, using a STATGRAPHICS software package. Estimated communalities were placed on the diagonal of the matrix in the principal factor extraction. Varimax rotation was applied to the factor matrix to improve factor interpretation.

Table 19. Aircraft / Ship Data Factor Analysis

Variable	Communality	Factor	Eigenvalue via P-Fctr	Eigenvalue via P-Cmpt	Explained % Variance	Explained % Total
ON TIME	0.97337	1	5.75963	5.80	55.2	55.2
LATE TON	0.97578	2	2.59462	2.75	24.9	80.1
AIR TON	0.89977	3	1.17421	1.59	11.3	91.3
DELQ TON	0.96129	4	.75245		7.2	98.6
SWT						
INFANTRY	0.86806	5	.11335		1.1	99.6
CBT SPT	0.98892	6	.02593		.2	99.9
CBT SVC SPT	0.99150	7	.01080		.1	100.0
RESUPPLY	0.92901	8	-.00049		.0	100.0
NATO						
ARMOR	0.73128	9	-.00981		.0	100.0
INFANTRY	0.63986	10	-.02996		.0	100.0
CBT SPT	0.40770	11	-.05937		.0	100.0
CBT SVC SPT	0.83678	12	-.12803		.0	100.0

Variable	Estimate of Communality (after factor extraction): 2 Factors	3 Factors
ON TIME TONS (TOTAL)	0.93066	0.93390
LATE TON DAYS (TOTAL)	0.92613	0.92625
AIR TONS MOVED (TOTAL)	0.86895	0.86895
DELINQUENT TONS (TOTAL)	0.93693	0.94015
SOUTHWEST ASIA ON TIME TONS		
INFANTRY	0.49408	0.53323
COMBAT SUPPORT	0.95534	0.95764
COMBAT SVC SUPPORT	0.96923	0.97520
RESUPPLY	0.75875	0.83929
NATO ON TIME TONS		
ARMOR	0.68626	0.73789
INFANTRY	0.09565	0.65642
COMBAT SUPPORT	0.04525	0.43495
COMBAT SVC SUPPORT	0.68702	0.72459

Table 20. Aircraft / Ship Two and Three Factor Matrices after Varimax Rotation

	Two Factor	
Variable/Factor	1	2
ON TIME TONS (TOTAL)	0.93895	0.22145
LATE TON DAYS (TOTAL)	-0.93156	-0.24151
AIR TONS MOVED (TOTAL)	0.10158	0.92662
DELINQUENT TONS (TOTAL)	-0.89998	-0.35631
SOUTHWEST ASIA		
ON TIME TONS (SWT)		
INFANTRY	-0.17312	0.68126
COMBAT SUPPORT	0.97450	0.07542
COMBAT SVC SUPPORT	0.98332	0.04810
RESUPPLY	0.87035	-0.03513
NATO ON TIME TONS (NT)		
ARMOR	0.17237	0.81027
INFANTRY	0.27721	-0.13714
COMBAT SUPPORT	0.20228	-0.06586
COMBAT SVC SUPPORT	0.07558	0.82541

	Three Factor		
Variable/Factor	1	2	3
ON TIME TONS (TOTAL)	0.92978	0.17714	0.19503
LATE TON DAYS (TOTAL)	-0.93537	-0.18872	-0.12534
AIR TONS MOVED (TOTAL)	0.16848	0.91233	-0.09061
DELINQUENT TONS (TOTAL)	-0.90150	-0.31273	-0.17219
SOUTHWEST ASIA			
ON TIME TONS (SWT)			
INFANTRY	-0.15297	0.70919	0.08295
COMBAT SUPPORT	0.97156	0.01717	0.11586
COMBAT SVC SUPPORT	0.98313	-0.01411	0.09199
RESUPPLY	0.90066	-0.11709	-0.11996
NATO ON TIME TONS (NT)			
ARMOR	0.26771	0.76417	-0.28680
INFANTRY	0.13634	-0.05427	0.79680
COMBAT SUPPORT	0.08893	0.00427	0.65347
COMBAT SVC SUPPORT	0.10286	0.83833	0.10589

From the data, there are at least two factors that seem to emerge. The first factor again seems to have a large amount of common variance lodged in the output variables which reflect timeliness, namely MOEs 1, 2 and 4. Also note the absence in that first factor of any weighting on MOE 3, 6, 13, or 14. MOE 3 is Air Tons moved, and MOEs 6, 13 and 14 (SWA Infantry, NATO Combat Support and NATO Combat Services Support, respectively) are all cargos which are moved more by air than other individual cargo MOEs (See Appendix G for a sample MINOTAUR output report). The second factor has large weights for MOE 3, 6, and 14, and seems to capture airlift activity levels.

These categorizations make sense since sealift, which has a much greater share of the lift tonnage, will be responsible for a the largest share of timely strategic lift. Thus Factor 1, timely strategic lift, is affected by ships much more than aircraft (explaining the low levels of MOE 3 on the first factor). Factor 2, the airlift movements, will affect timely lift to a much smaller degree (especially over a 60 day conflict).

The high factor weightings of MOEs 12 and 13 on the third column of the 3 factor matrix require considering that the correct dimensionality may actually be 3. The size of the third eigenvalue (greater than 1, explaining over 10 % of the variance) also seems to support this. Unfortunately, MOEs 12 and 13, (NATO Infantry and Combat Support), don't

seem to be so unique as to put them in a factor group all by themselves. This leaves two choices: Throw out these points or have a dimensionality of three. It was decided to keep two dimensions. To better visualize the first two proposed dimensions (timely lift and airlift activities), the first two factor scores were computed and plotted with the levels of ships / aircraft for a given run superimposed. This is shown in Figure 2.

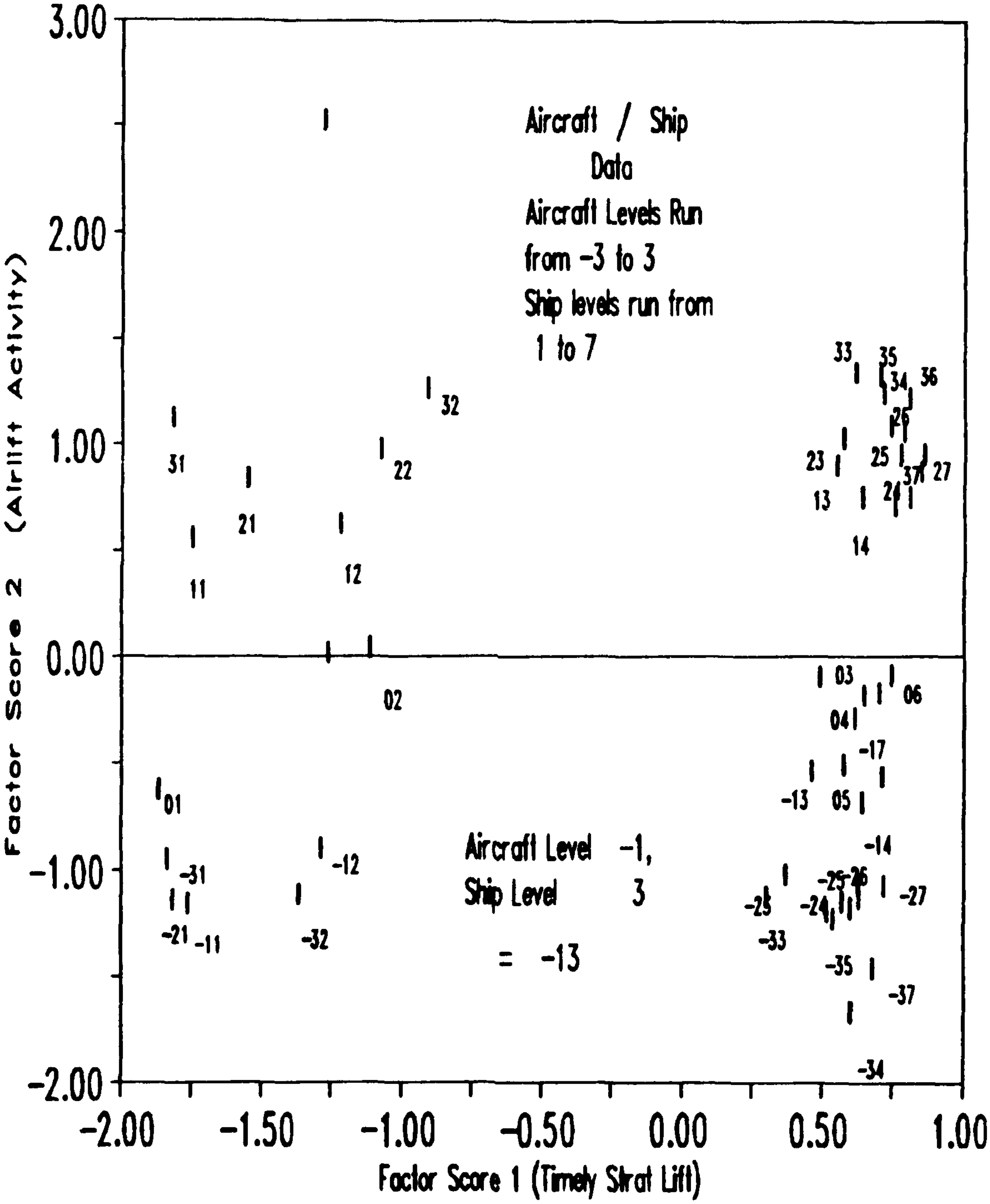

Figure 2. Rotated Factor Plot Showing Ship Levels Affecting Timely Lift and Aircraft Affecting Air Activity

The plot indicates a much larger increase in timely strategic lift occurs with changes of ships than with aircraft, and supports the assessment of the two dimensions of timely strategic lift and airlift activities. These two dimensions are not completely independent, but are nearly so. This makes sense in light of the fact ships carry 95 percent of wartime cargos.

After assessing the dimensionality in the aircraft ship data sec using 12 variables, it seemed logical that a similar plot could be made from the RSM data for 12 variables. The extra variable information was extracted, and Principal Components Analysis and Factor Analysis were run on the 12 variable problem for the RSM second order model data. The results are shown below in Tables 21 - 25.

Table 21. Principal Components Analysis for 12 Output Variables from Second Order Model

Principal Component Number	Eigen Value	Percent of Variance	Cumulative Percentage
1	8.261	71.83959	71.83959
2	1.768	14.73106	86.57065
3	0.6428	5.35700	91.92765
4	0.4751	3.95923	95.88688
5	0.2271	1.89262	97.77949
6	0.0991	.82647	98.60596
7	0.0644	.53673	99.14269
8	*	.40369	99.54639
9	*	.29641	99.84280
10	*	.08751	99.93031
11	*	.05911	99.98942
12	*	.01058	100.00000

* = insignificant

Table 22. Loadings Matrix for 12 MOE Data from Second Order Model (First 6 Principal Components)

MOE	1	2	3	4	5	6
	Loadings on Principal Component:					
ON TIME	-0.334	-0.006	0.026	-0.002	0.014	-0.021
LATE TON	0.286	-0.158	0.046	-0.002	0.058	-0.009
AIR TON	-0.238	-0.156	-0.133	0.100	0.061	0.015
DELQ TON	0.267	-0.143	0.134	-0.007	0.039	-0.039
SWA						
INFANTRY	-0.300	0.131	-0.024	-0.022	-0.003	-0.058
CBT SPT	-0.297	0.062	0.113	0.009	0.073	0.033
CBT SVC SPT	-0.297	0.105	0.103	-0.004	0.007	0.021
RESUPPLY	-0.320	0.082	0.010	0.020	0.029	-0.020
NATO						
ARMOR	-0.257	-0.183	0.049	-0.050	-0.081	-0.001
INFANTRY	-0.241	-0.120	-0.064	-0.185	0.042	0.016
CBT SPT	-0.273	-0.156	0.061	0.065	-0.048	0.031
CBT SVC SPT	-0.295	-0.140	-0.007	0.043	0.001	-0.048

Table 23. Factor Analysis on 12 Output Variables from Second Order Model

MOE	Communality	Factor	Eigen Value	Explained % Variance	Cum
w1	0.99825	1	8.58731	74.1	74.1
w2	0.99053	2	1.72404	14.9	89.0
w3	0.96093	3	.60596	5.2	94.3
w4	0.98514	4	.36772	3.2	97.4
w6	0.98615	5	.17290	1.5	98.9
w7	0.95434	6	.07643	.7	99.6
w8	0.97497	7	.03824	.3	99.9
w9	0.98563	8	.01015	.1	100.0
w11	0.91868	9	-.00284	.0	100.0
w12	0.85682	10	-.00663	.0	100.0
w13	0.93232	11	-.00923	.0	100.0
w14	0.99009	12	-.03022	.0	100.0

where

w1 = ON TIME TONS (TOTAL)
w2 = LATE TON DAYS (TOTAL)
w3 = AIR TONS MOVED (TOTAL)
w4 = DELINQUENT TONS (TOTAL)
w5 = SOUTHWEST ASIA ON TIME TONS (SWT), ARMOR
w6 = SWT, INFANTRY
w7 = SWT, COMBAT SUPPORT
w8 = SWT, COMBAT SERVICES SUPPORT
w9 = SWT, RESUPPLY
w10 = SWT, AMMUNITION
w11 = NATO ON TIME TONS (NT), ARMOR
w12 = NT, INFANTRY
w13 = NT, COMBAT SUPPORT
w14 = NT, COMBAT SERVICES SUPPORT
w15 = NT, RESUPPLY
w16 = NT, AMMUNITION

Note: w5, w10, w15, w16 were dropped since their change over the runs was less than one percent, and including them would bias the analysis.

Table 24. Estimated Communality of 12 Variables from Second Order Model (After Extraction)

Variable	Est Communality
ON TIME TONS (TOTAL)	0.98962
LATE TON DAYS (TOTAL)	0.94341
AIR TONS MOVED (TOTAL)	0.71449
DELINQUENT TONS (TOTAL)	0.80770
SOUTHWEST ASIA	
ON TIME TONS (SWT)	
INFANTRY	0.94962
COMBAT SUPPORT	0.80493
COMBAT SERVICES SUPPORT	0.87173
RESUPPLY	0.96124
NATO ON TIME TONS (NT)	
ARMOR	0.85369
INFANTRY	0.60630
COMBAT SUPPORT	0.85989
COMBAT SERVICES SUPPORT	0.94872

Table 25. Varimax Rotated Factor Matrix for 12 Variable Second Order Model

	Factor	
Variable	1	2
ON TIME TONS (TOTAL)	0.73364	0.67186
LATE TON DAYS (TOTAL)	-0.94899	-0.20696
AIR TONS MOVED (TOTAL)	0.22385	0.81510
DELINQUENT TONS (TOTAL)	-0.87521	-0.20424
SOUTHWEST ASIA		
ON TIME TONS (SWT)		
INFANTRY	0.92817	0.29684
COMBAT SUPPORT	0.77726	0.44811
COMBAT SVC SUPPORT	0.86519	0.35098
RESUPPLY	0.87322	0.44579
NATO ON TIME TONS (NT)		
ARMOR	0.22337	0.89655
INFANTRY	0.31297	0.71299
COMBAT SUPPORT	0.30682	0.[illegible]7507
COMBAT SVC SUPPORT	0.38047	0.89664

The principal component analysis would indicate a dimensionality of 2 due to eigenvalue size, and the factor analysis seems to confirm this. The FA eigenvalues are nearly identical with those from PCA and most all MOEs have high loading on just the first two factors. Looking at the Factor matrix, one can again see airlift movements loading on the second factor rather than the first, again perhaps reflecting a strategic lift factor and an airlift movements factor.

Since the 7 types of aircraft were varied individually in the RSM runs, their group effect is not as easy to plot as it was in the aircraft / ship case. However, three runs of the group had been made with the aircraft at their mean level (a coded level of 0) while the warning day variable was changed from -1 to 1, and these three points are labelled in Figure 3. This helps interpret the dimensionality assessment of 2 for the RSM data, in a similar fashion to the assessment for the Aircraft / Ship data.

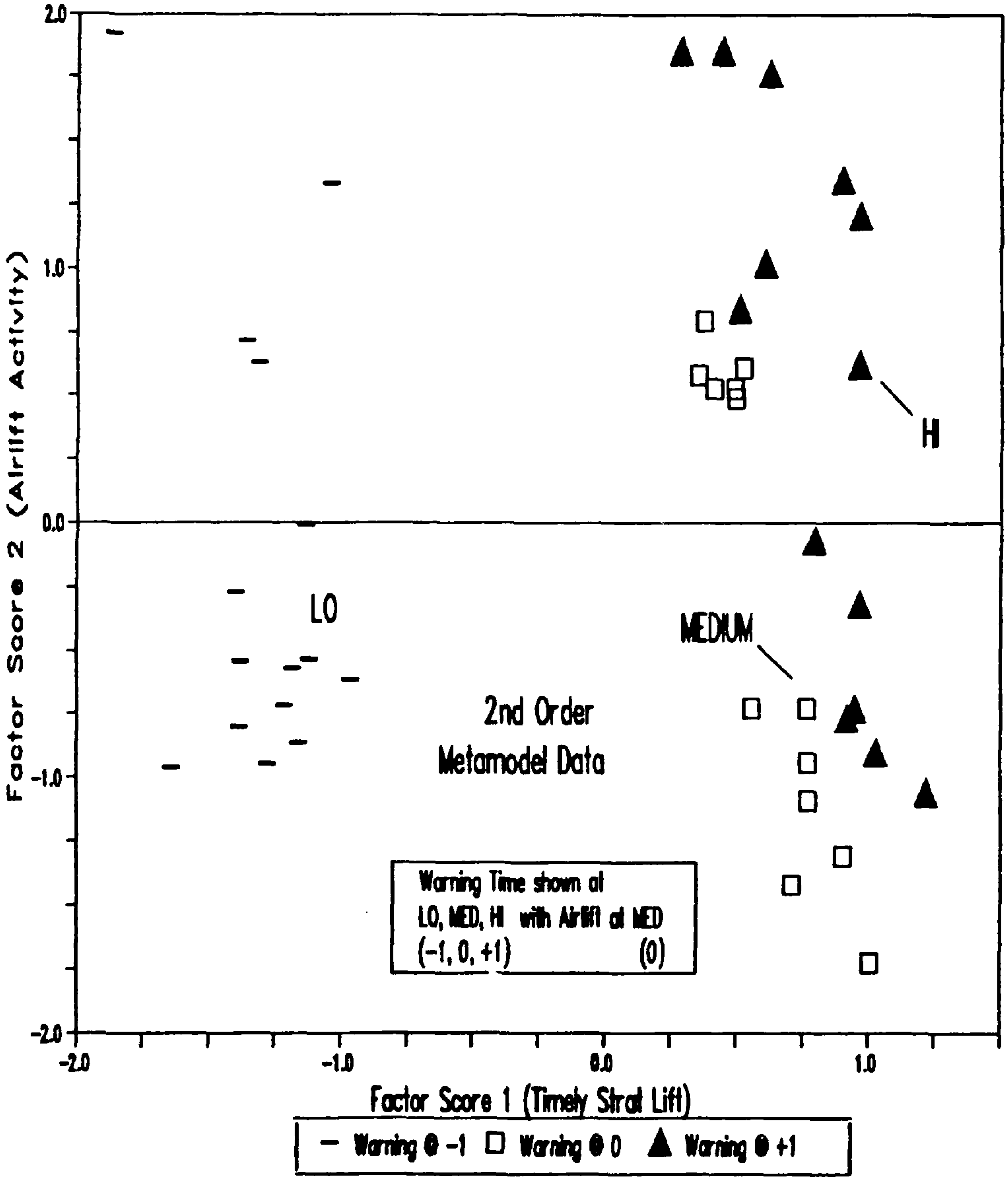

Figure 3. Rotated Factor Plot Showing Warning Time Affecting Timely Lift and Aircraft Affecting Air Activity

In summary, there appeared to be two dimensions, possibly three, for the aircraft / ship data set. There seemed to be two dimensions to the second order model data from RSM when all 12 variables were considered in the analysis (recall there seemed to be only one dimension to the RSM data when just the 4 most aggregate MOEs were considered). The two underlying factors for both the RSM data set and the Aircraft / Ship data set seem to be a timely strategic lift factor and an airlift activities factor.

V. RESULTS

The objective of this effort was to provide a methodology for generating a valid response surface for the MINOTAUR mobility model. Sub-objectives included defining measures of effectiveness and using multivariate analysis to reduce the dimensionality of the data and interpret results.

Four aggregate measures of effectiveness were proposed from available model data: On Time Tons, Late Ton Days, Air Tons Moved, and Delinquent Tons.

After group and factor screenings, a linear metamodel was found which had good Adjusted R-Squared values, but residual plots and validation testing proved the first order metamodel inadequate. A second order metamodel was created after making runs from a small composite design. This fit much better in the 9 validation runs, allowing a consistent accuracy in prediction of better than ± 10 percent. The metamodel was used with the four new measures of effectiveness, and of the four, only the metamodel using Late Ton Days behaved worse than ± 10 percent.

Multivariate data analysis was conducted on the output data from the RSM runs, which showed a dimensionality of one among the four output measures. A linear combination of these four MOEs was found through principal component analysis. This new measure, the Strategic Lift Index, captured the essence of the other four MOEs and was shown to be accurate to ± 10 percent in matching predicted vs actual

values in 9 validation runs.

These 4 MOEs from the RSM work and 12 other less aggregate MOEs were subjected to Principal Component Analysis and Factor Analysis for assessments of dimensionality and underlying factors. Another data set, created from changing ship and aircraft in the database at 7 different levels, was also subjected to multivariate analysis. The analysis showed a dimensionality of two or possibly three, with two main underlying factors: timely strategic lift and air movements.

The primary objective of demonstrating a methodology for creating a valid metamodel for MINOTAUR was achieved. The secondary objectives of finding new measures of effectiveness were also achieved. In addition to these objectives, the multivariate analysis provided an enlightening insight into the interrelations of the model processes and the output data, showing two underlying dimensions: timely strategic lift and airlift activity.

VI. INSIGHTS / RECOMMENDATIONS

Multivariate analysis proved a powerful tool in assessing underlying dimensionality, helping to bolster confidence in the aggregate measures of effectiveness developed in this thesis.

Developing a response surface was relatively straight forward. The small composite design used for the second order model was easy to generate and use. The designs for the group and factor screenings were well documented and also easy to construct. Another possibility to consider for future designs is to use a fold-over technique rather than a saturation technique when dealing with a fractional design. A higher resolution design can be created in the same number of runs.

Several areas of further study could be undertaken using MINOTAUR and building a response surface.

First, the MINOTAUR model itself still needs to be fully validated. Work on this is ongoing at OASD/PA&E. Any attempt to promote the use of a metamodel needs to show a valid base model for credibility.

Second, validated, current data from other studies or models could be used to improve the metamodel accuracy. For instance, if a particular study showed some wartime limitation on some characteristic of an aircraft, restricting its use well below the levels in the planning factors currently used, that change should be incorporated

into the MINOTAUR database used for the metamodel. These changes could help establish the credibility many aggregate models lack.

Third, if credibility is established, cost studies could be done using the response function from MINOTAUR as a constraint in an optimization problem, with a minimum cost objective function being realized while maintaining a set airlift delivery capability.

Fourth, MINOTAUR could be enhanced and a response surface could be constructed on the enhanced program. Several enhancements include adding the capability to simulate attrition in the model and adding a convoy capability for the ships. Both of these could provide more model credibility and provide new factors to consider for a response surface.

In addition to recommendations for further study, several closing observations should be made. The metamodel, while not a replacement for the original, is a very powerful tool for quick analysis. Hopefully this work will show some of the many computer model users in DoD an organized approach to applying an experimental design and developing a metamodel, as well as the usefulness of multivariate analysis in paring data down to its more interpretable elements. Key aspects, as with any problem solving exercise, are a good definition of the problem and a lot of early planning and data gathering. This will aid in creating a good experimental design and saving much

computationally intensive work later. It has also helped to develop a network of contacts to facilitate information flow when schedule deadlines are near.

Appendix A

Group Screening Data

Table 26. Output Data From 4 Group Screening Runs

Run No.	On Time Tons	Late Ton Days	Air Tons Moved	Delinquent Tons
1	4.21349E+06	2.43494E+06	7.50637E+05	20865.0
2	4.17639E+06	2.73501E+06	4.82796E+05	22864.9
3	4.11426E+06	3.16082E+06	4.67753E+05	70218.2
4	4.28144E+06	1.26542E+06	7.77395E+05	23815.4
5	4.13465E+06	2.96913E+06	4.93004E+05	20865.0
6	4.20386E+06	2.64549E+06	7.11406E+05	20865.0
7	4.36274E+06	1.13681E+06	8.18318E+05	24440.4
8	4.09878E+06	3.44282E+06	4.53584E+05	20865.0

Table 27. Design Matrix for 8 Run Group Screen (Plackett-Burman Resolution III)

Run No.	A/C No.	UTE RATE	DELAY TIME	WARNING TIME			
1	1	1	1	-1	1	-1	-1
2	-1	1	1	1	-1	1	-1
3	-1	-1	1	1	1	-1	1
4	1	-1	-1	1	1	1	-1
5	-1	1	-1	-1	1	1	1
6	1	-1	1	-1	-1	1	1
7	1	1	-1	1	-1	-1	1
8	-1	-1	-1	-1	-1	-1	-1

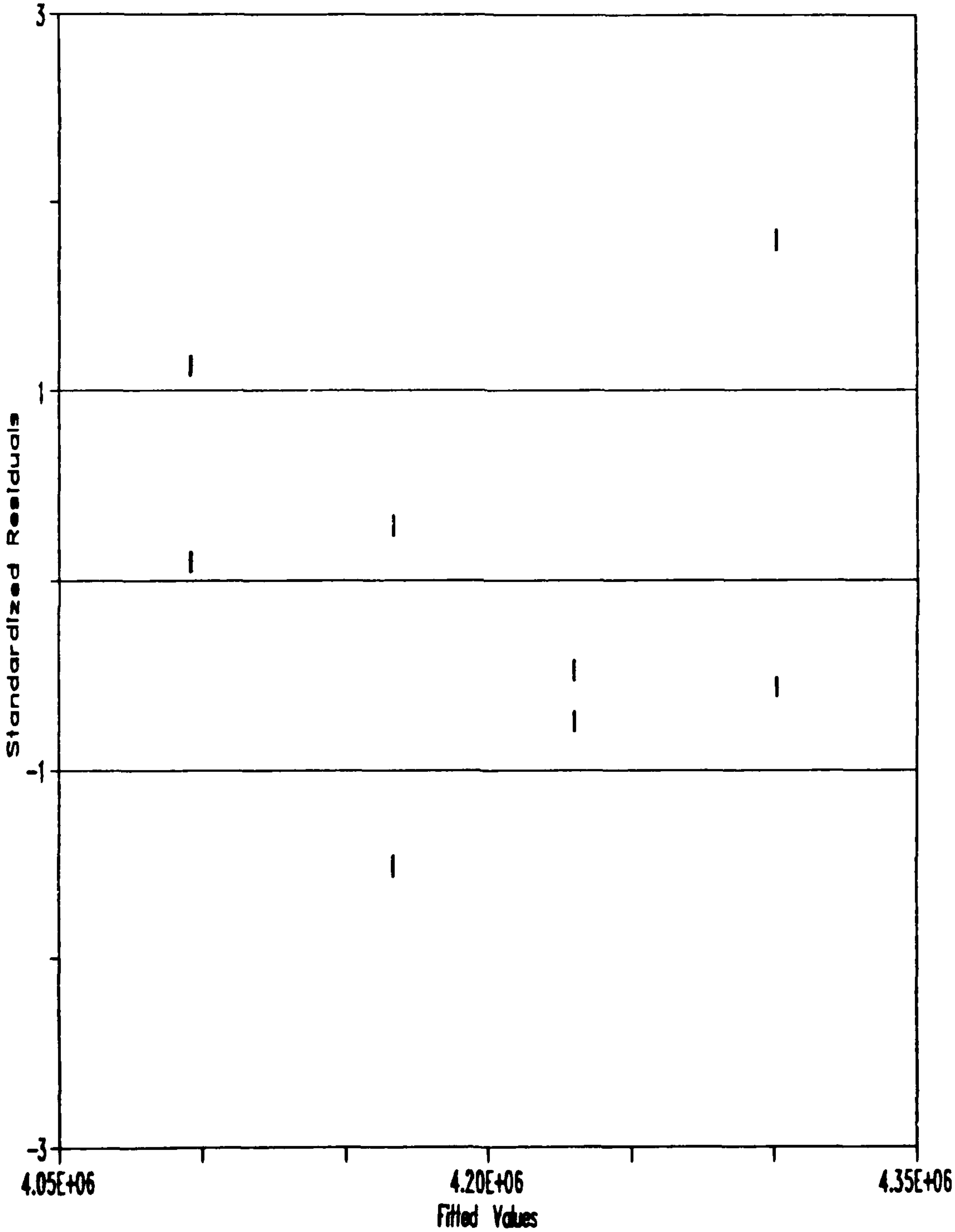

Figure 4 . Group screen Standardized Residuals

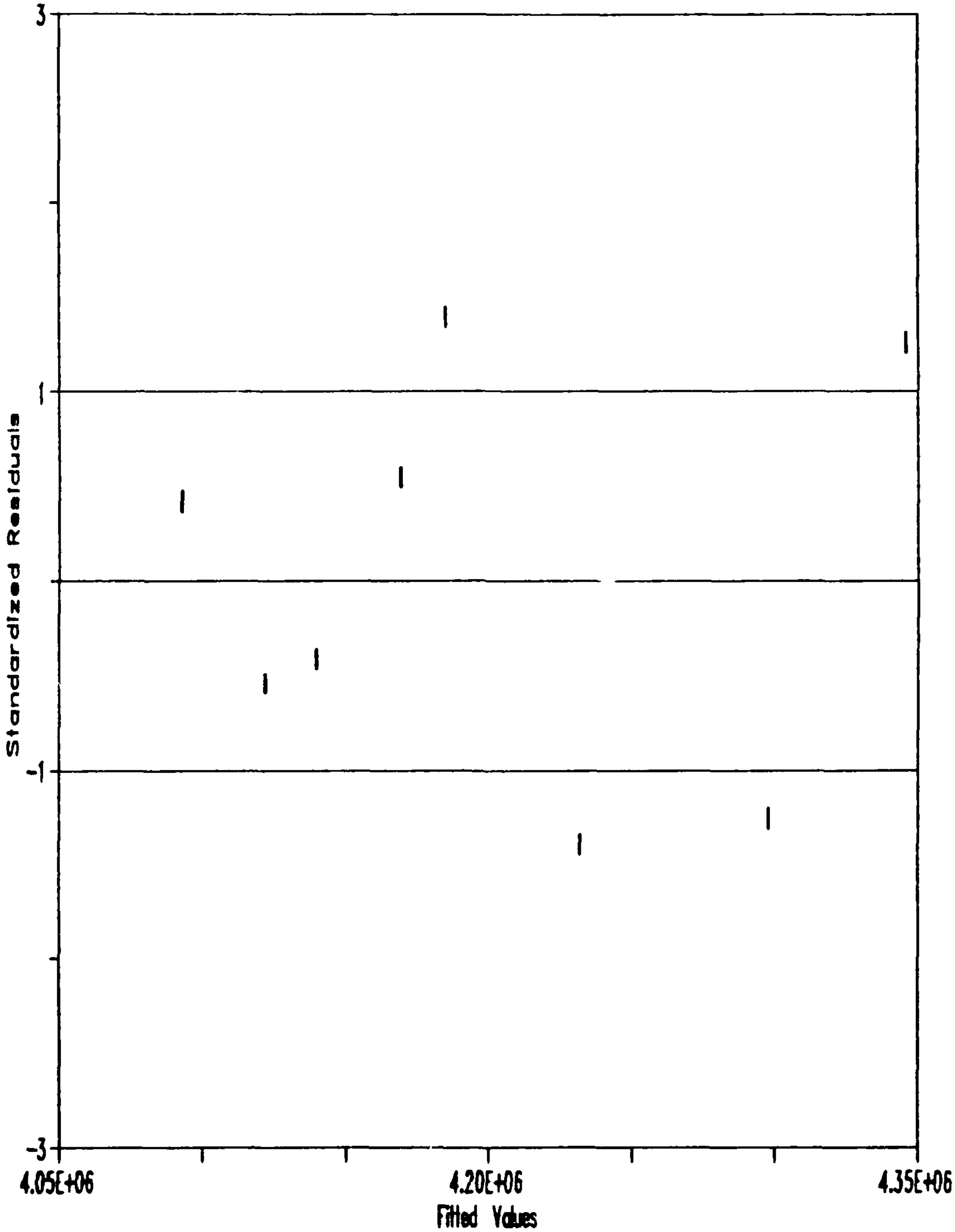

Figure 5. Standardized Residuals After Removing 2 Groups

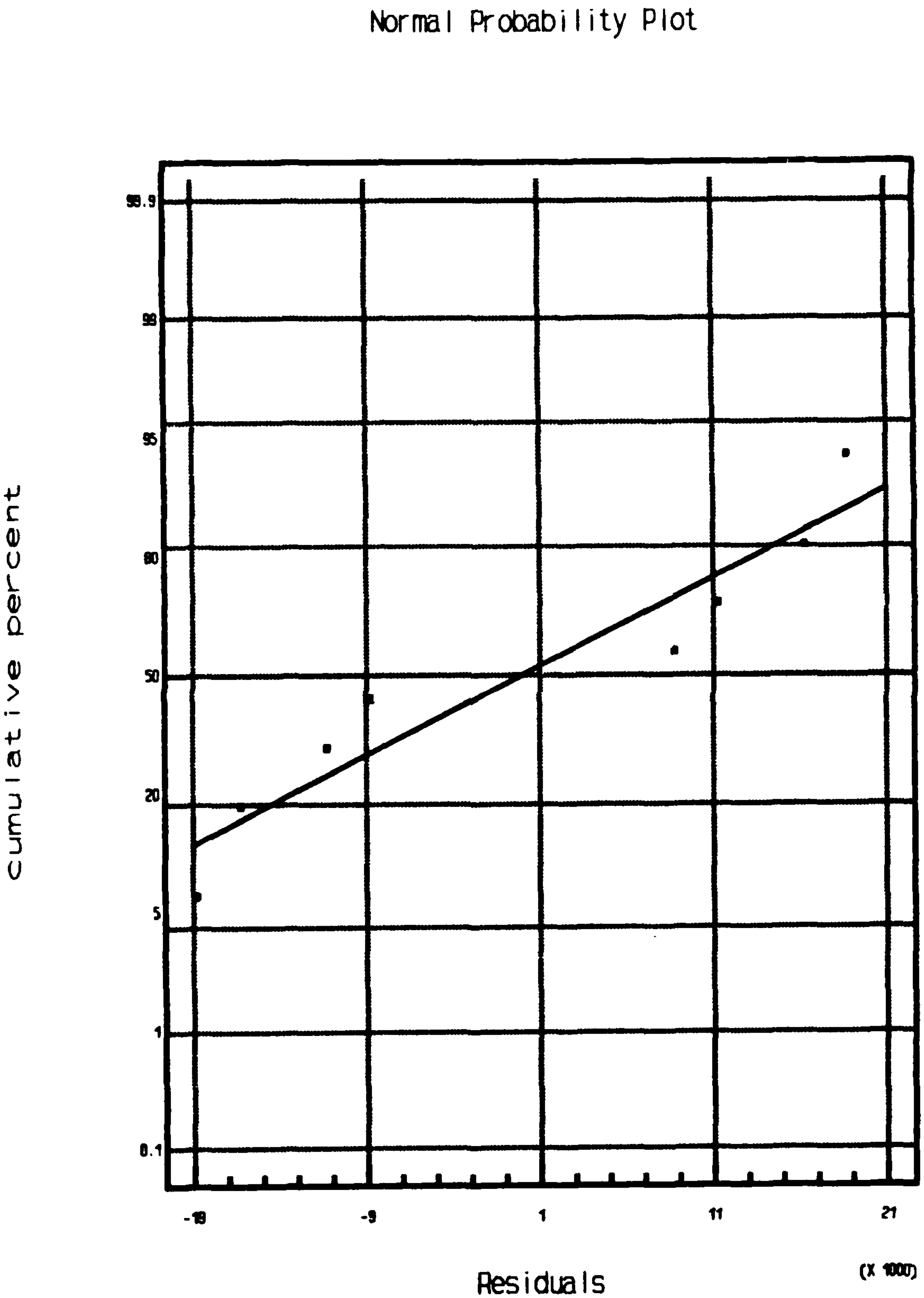

Figure 6. Normality Plot for Late Ton Days Before Group Screen

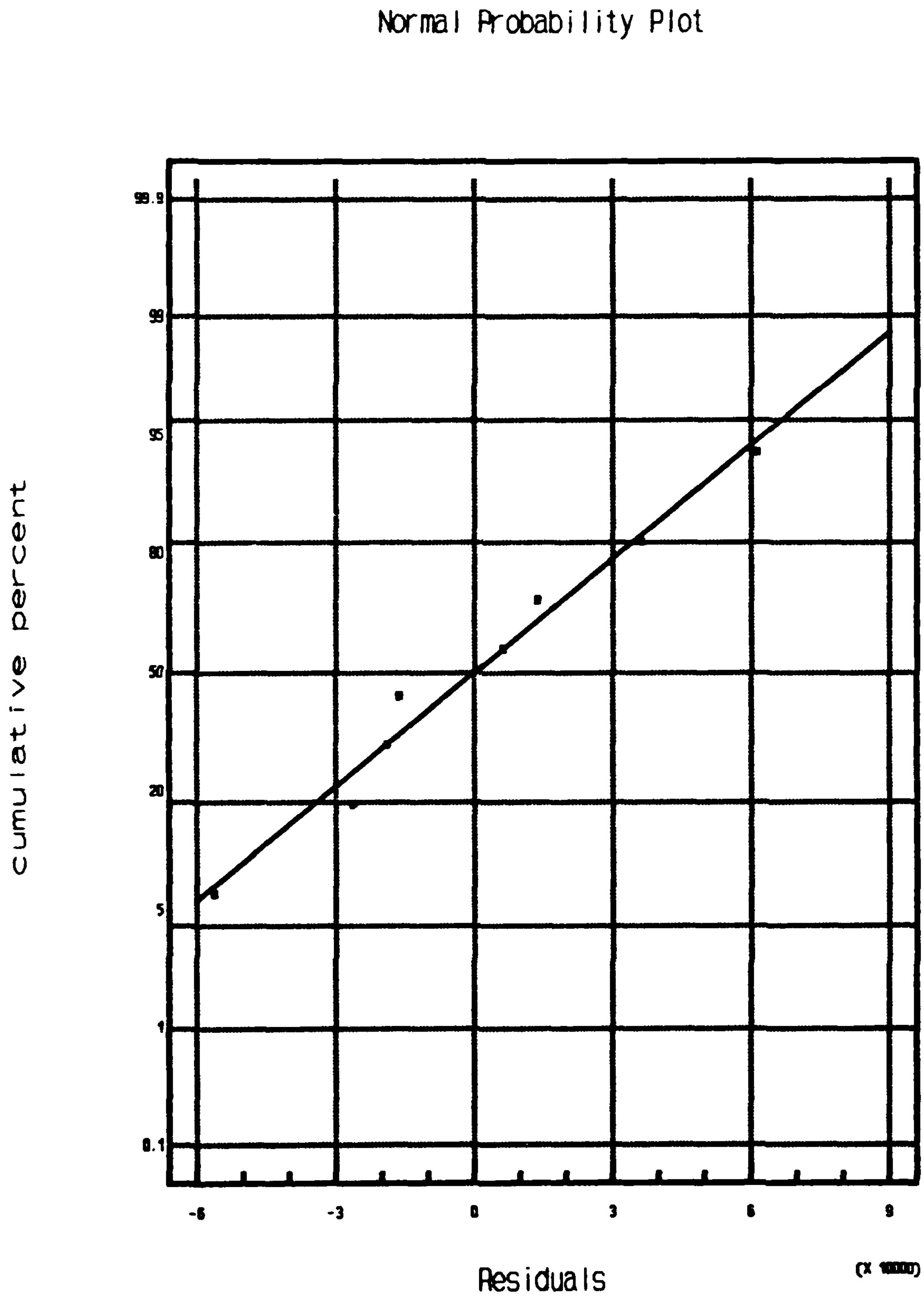

Figure 7. Normality Plot for On Time Tons after Screen

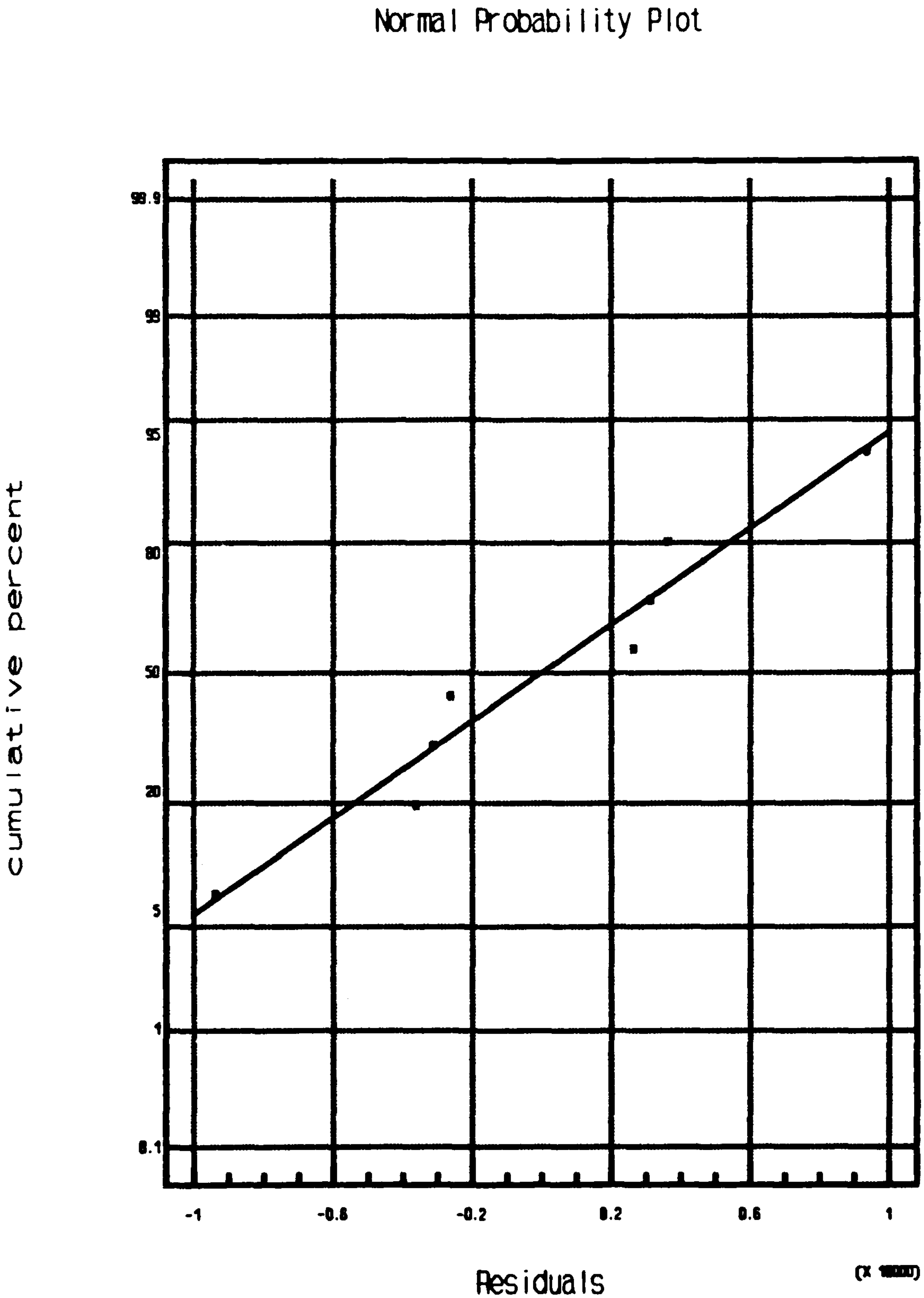

Figure 8. Normality Plot for Air Tons Moved before Screen

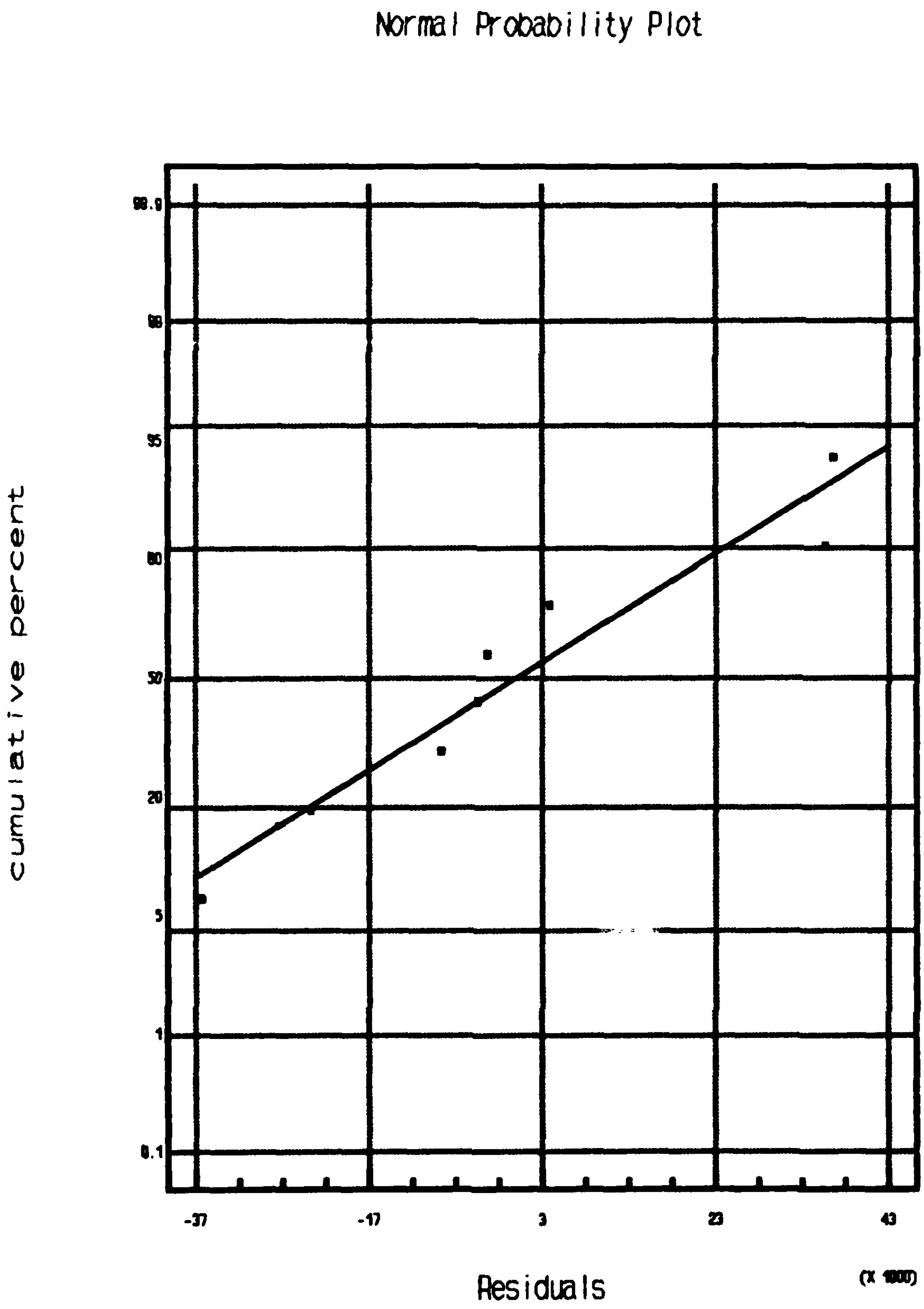

Figure 9. Normality Plot for Air Tons Moved after Screen

Appendix B

Factor Screening Outputs

Table 28. Output Data From 16 Factor Screening Runs

Run No.	On Time Tons	Late Ton Days	Air Tons Moved	Delinquent Tons
1	3787547.482	4580784.600	531688.180	470962.597
2	3842568.402	3874408.700	635786.898	391078.883
3	3786263.586	4446344.300	574269.024	454528.997
4	3881622.536	3747365.400	666981.799	350140.886
5	3820309.428	4071480.400	600013.590	443273.350
6	3866348.490	3644488.700	675710.844	357796.739
7	3872464.317	3520573.700	698841.322	338842.801
8	3826852.578	3784319.100	658045.872	381461.632
9	4063713.678	2175021.600	568597.272	217058.562
10	4047997.854	2148480.800	580590.492	200357.820
11	4270289.262	1627150.300	617456.880	164533.273
12	4291233.474	1509587.900	648001.800	144954.741
13	4273125.138	1595014.300	627057.588	161758.042
14	4355174.520	1456216.500	680939.232	144033.567
15	4282297.812	1633373.700	601313.022	185671.950
16	4442689.302	1207325.500	806176.470	125038.068

Table 29. Factor Screening Model for On Time Tons

LEAST SQUARES LINEAR REGRESSION OF ON TIME TONS

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	4.0444E+06	2.0115E+04	201.06	0.0000	
WARNING	2.0891E+05	2.0115E+04	10.39	0.0000	.8245
C-141	3.7308E+04	2.0115E+04	1.85	0.0884	.8417
WB CRAF	4.8002E+04	2.0115E+04	2.39	0.0344	.8837

CASES INCLUDED	16	MISSING CASES	0
DEGREES OF FREEDOM	12		
OVERALL F	39.00	P VALUE	0.0000
ADJUSTED R SQUARED	0.8837		
R SQUARED	0.9070		
RESID. MEAN SQUARE	6.474E+09		

Table 30. Factor Screening Model for Late Ton Days

LEAST SQUARES LINEAR REGRESSION OF LATE TON DAYS

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	2.8139E+06	5.6314E+04	49.97	0.0000	
WARNING	-1.1448E+06	5.6314E+04	-20.33	0.0000	.9158
C-17	-1.4235E+05	5.6314E+04	-2.53	0.0281	.9258
C-141	-1.2937E+05	5.6314E+04	-2.30	0.0422	.9343
WB CRAF	-1.9977E+05	5.6314E+04	-3.55	0.0046	.9666

CASES INCLUDED	16	MISSING CASES	0
DEGREES OF FREEDOM	11		
OVERALL F	109.4	P VALUE	0.0000
ADJUSTED R SQUARED	0.9666		
R SQUARED	0.9755		
RESID. MEAN SQUARE	5.074E+10		

Table 31. Factor Screening Model For Air Tons Moved

LEAST SQUARES LINEAR REGRESSION OF AIR TONS MOVED

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	6.3572E+05	3513.9	180.92	0.0000	
C-17	3.3312E+04	3513.9	9.48	0.0000	.2290
C-141	2.3169E+04	3513.9	6.59	0.0001	.3262
WB CRAF	3.2795E+04	3513.9	9.33	0.0000	.6098
NB CRAF	2.3632E+04	3513.9	6.73	0.0001	.7667
KC-10	1.8588E+04	3513.9	5.29	0.0005	.8743
C-5	1.4846E+04	3513.9	4.22	0.0022	.9532

CASES INCLUDED	16	MISSING CASES	0
DEGREES OF FREEDOM	9		
OVERALL F	51.92	P VALUE	0.0000
ADJUSTED R SQUARED	0.9532		
R SQUARED	0.9719		
RESID. MEAN SQUARE	1.976E+08		

Table 32. Factor Screening Model For Delinquent Tons

LEAST SQUARES LINEAR REGRESSION OF DELINQUENT TONS

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	2.8322E+05	6245.4	45.35	0.0000	
WARNING	-1.1529E+05	6245.4	-18.46	0.0000	.8870
C-17	-2.1360E+04	6245.4	-3.42	0.0076	.9138
C-141	-1.5072E+04	6245.4	-2.41	0.0390	.9257
WB CRAF	-1.5984E+04	6245.4	-2.56	0.0307	.9424
NB CRAF	-1.1468E+04	6245.4	-1.84	0.0995	.9499
C-5	-1.2039E+04	6245.4	-1.93	0.0860	.9606

CASES INCLUDED	16	MISSING CASES	0
DEGREES OF FREEDOM	9		
OVERALL F	61.99	P VALUE	0.0000
ADJUSTED R SQUARED	0.9606		
R SQUARED	0.9764		
RESID. MEAN SQUARE	6.241E+08		

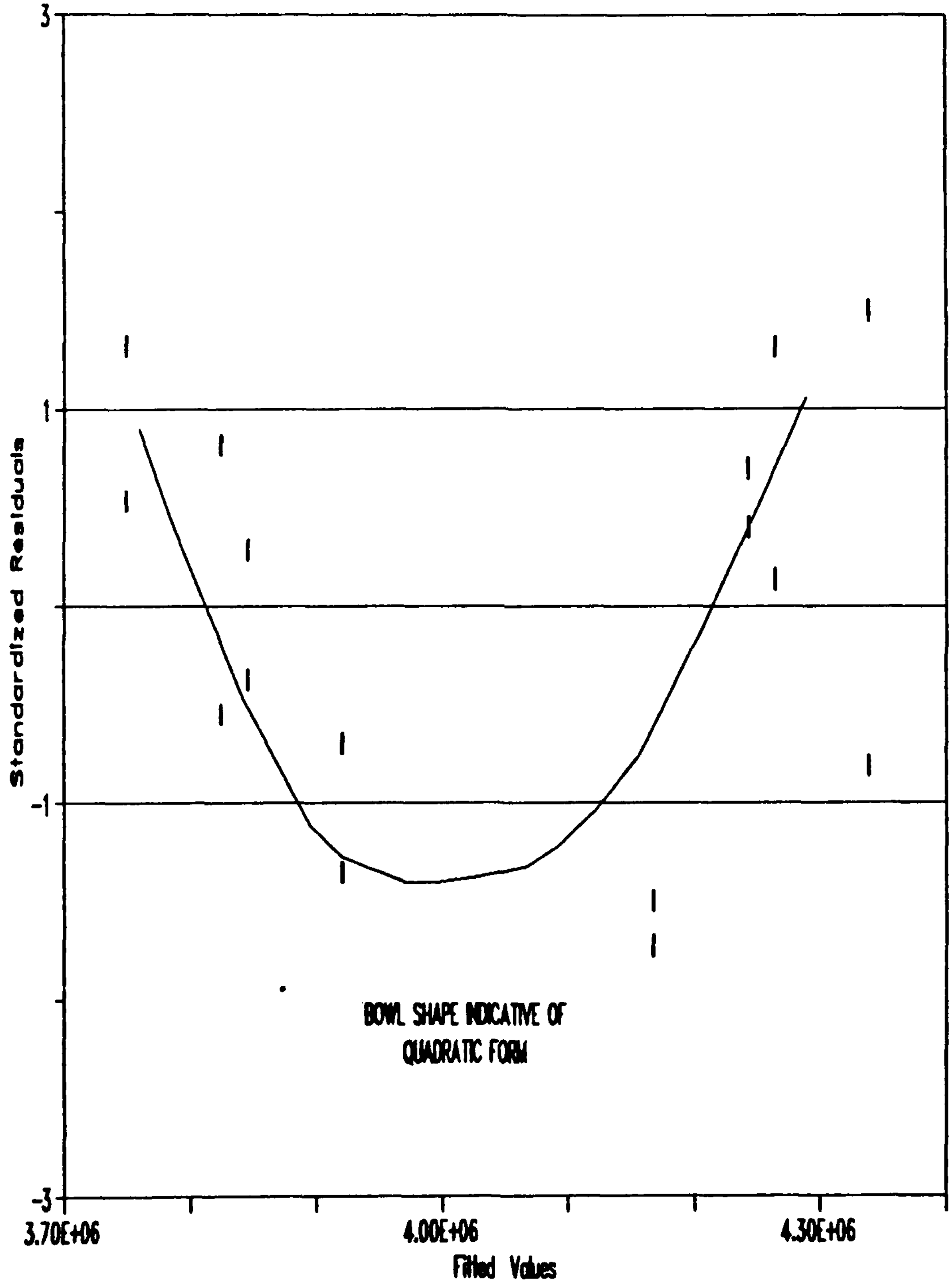

Figure 10 . Standard Residuals for On Time Tons, Factor Screen

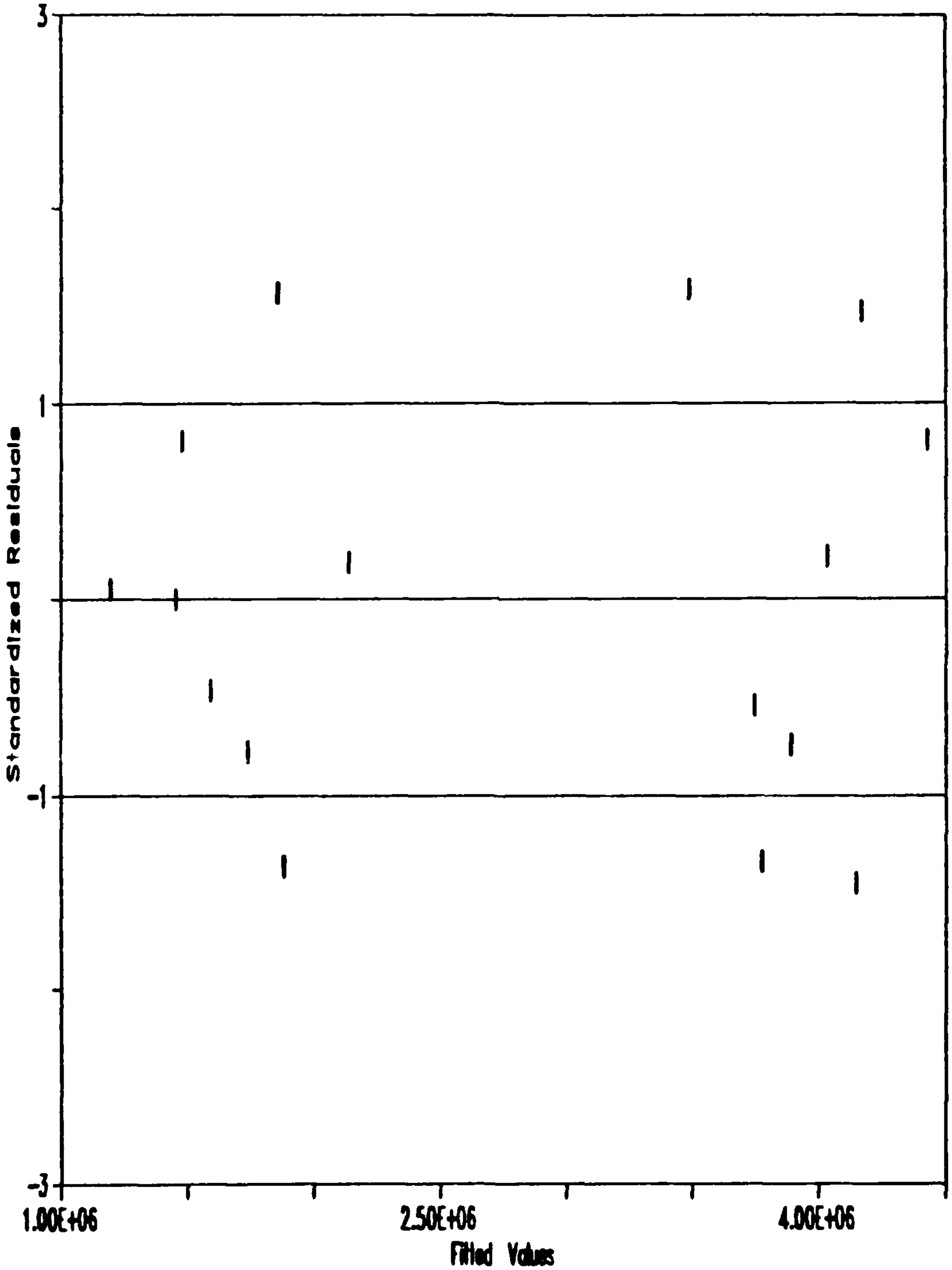

Figure 11 Standard Residuals for Late Ton Days, Factor Screen

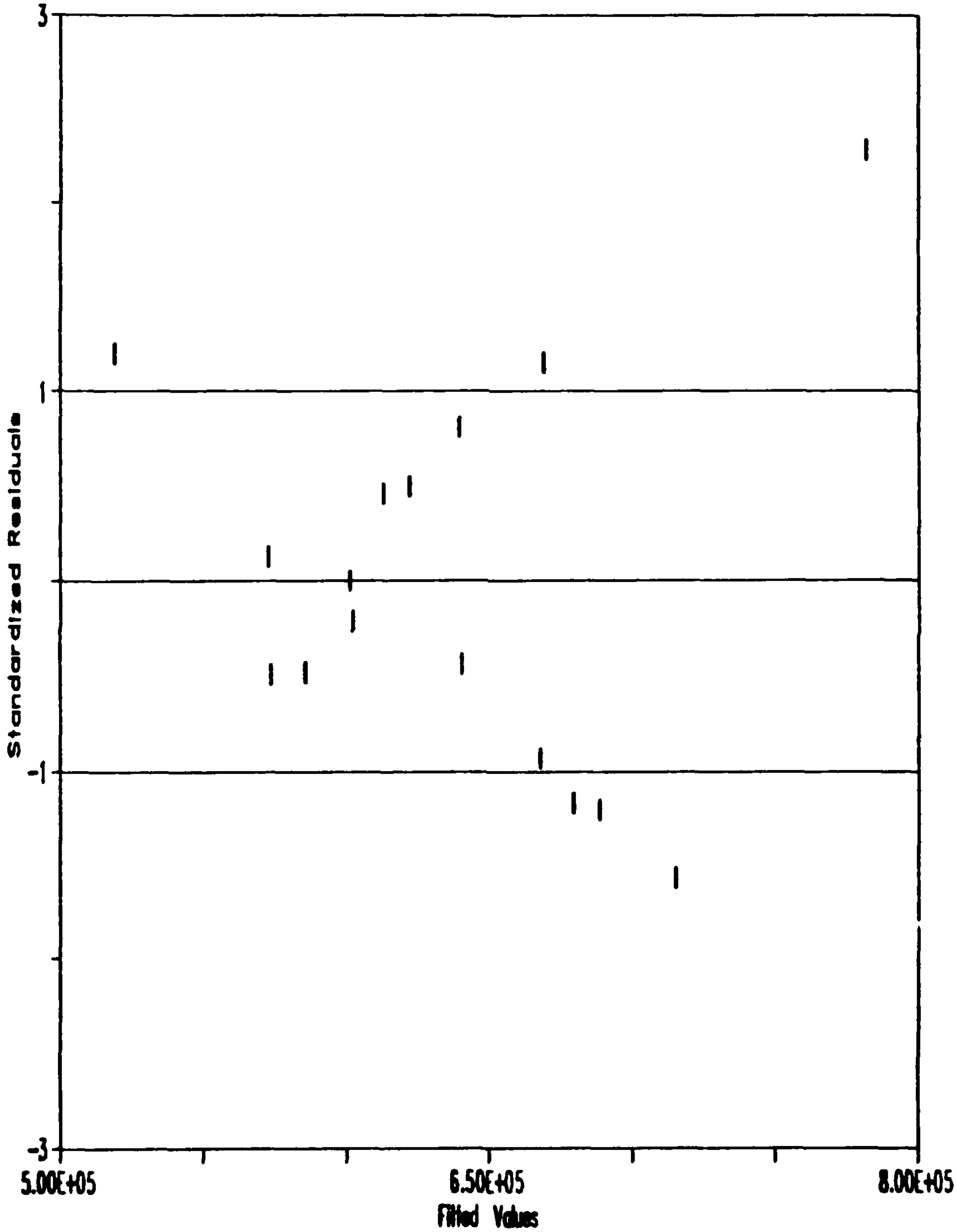

Figure 12. Standard Residuals for Air Tons Moved, Factor Screen

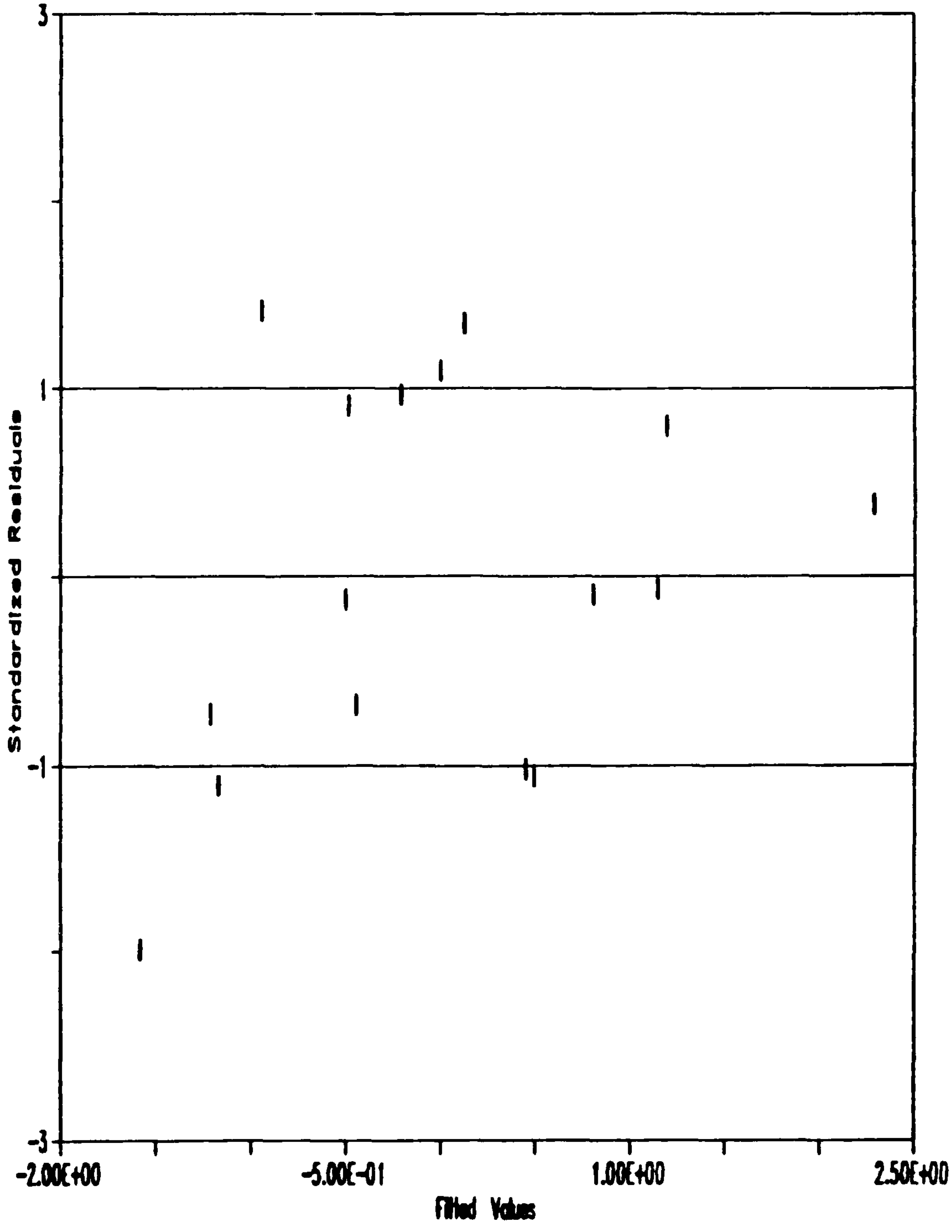

Figure 13. Standard Residuals for Delinquent Tons, Factor Screen

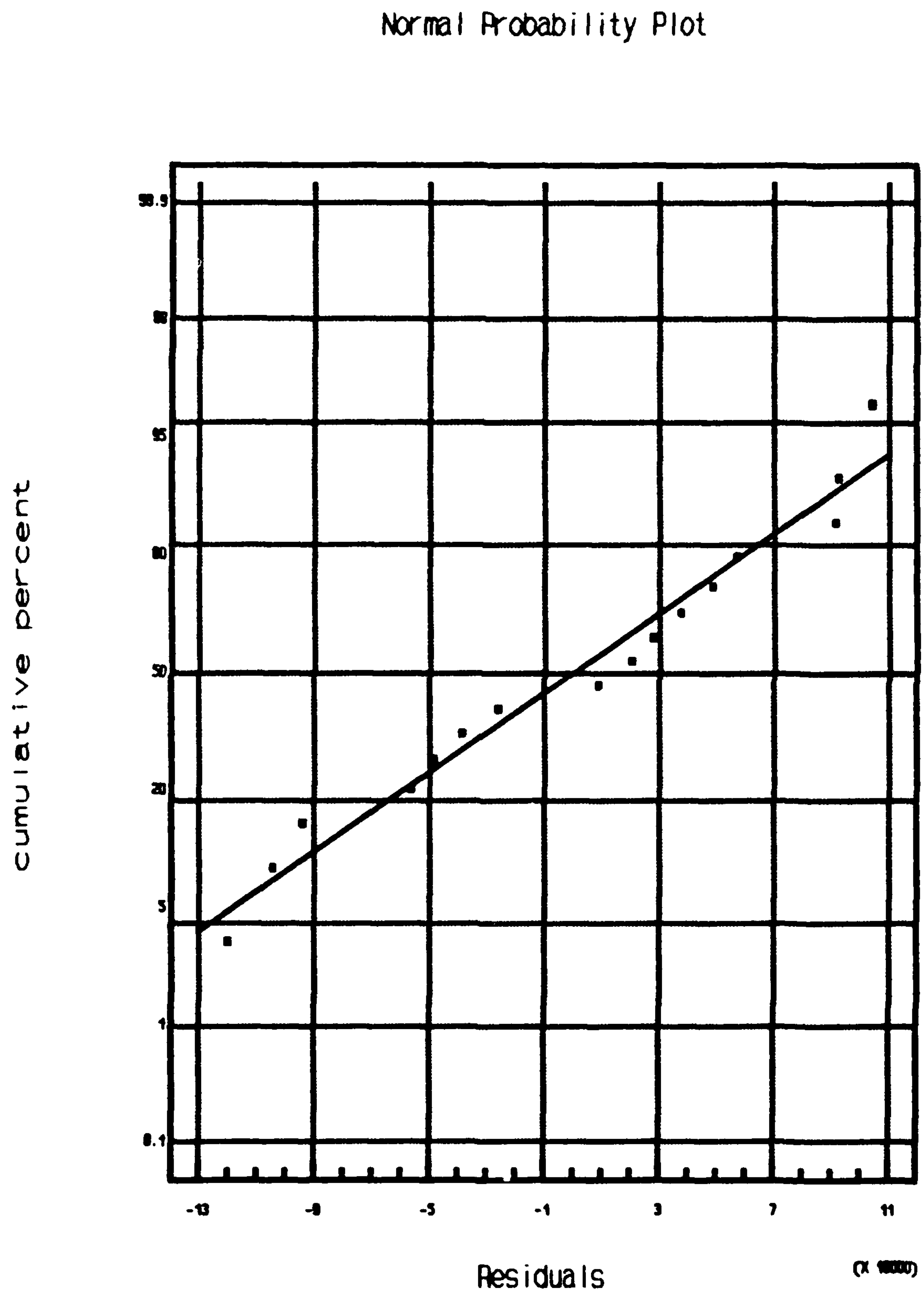

Figure 14. Normality Plot for On Time Tons, Factor Screen

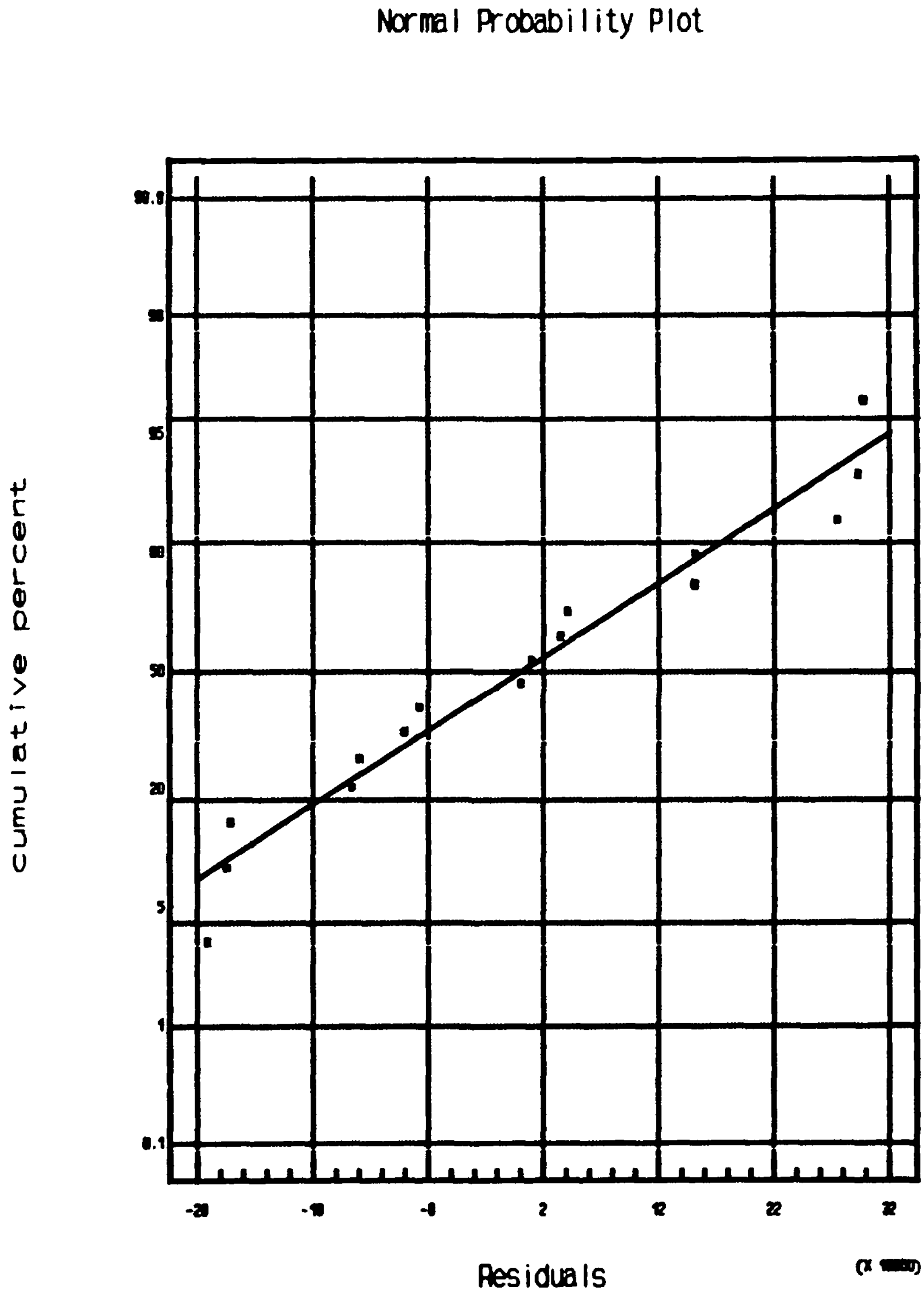

Figure 15. Normality Plot for Late Ton Days, Factor Screen

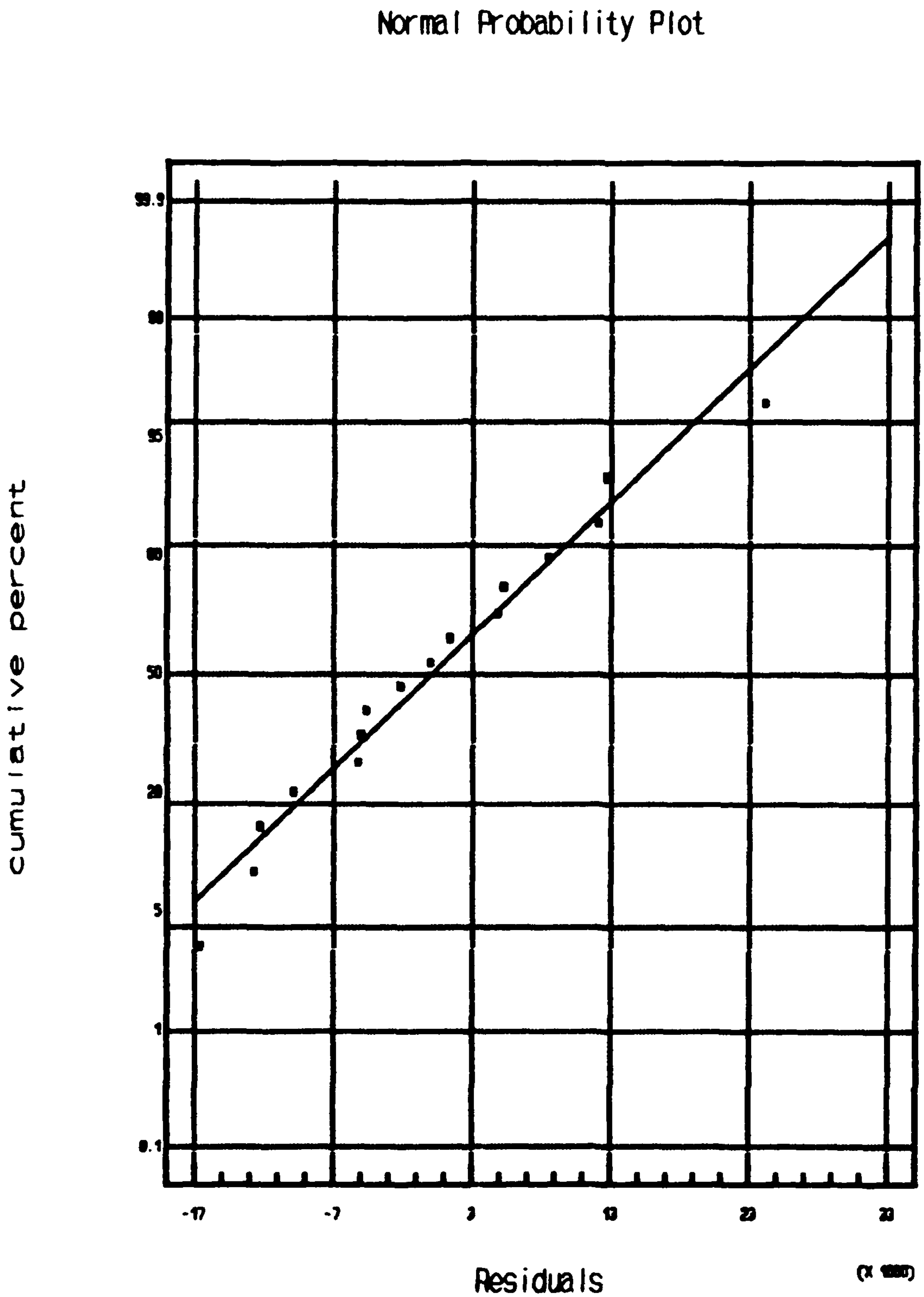

Figure 16. Normality Plot for Air Tons Moved, Factor Screen

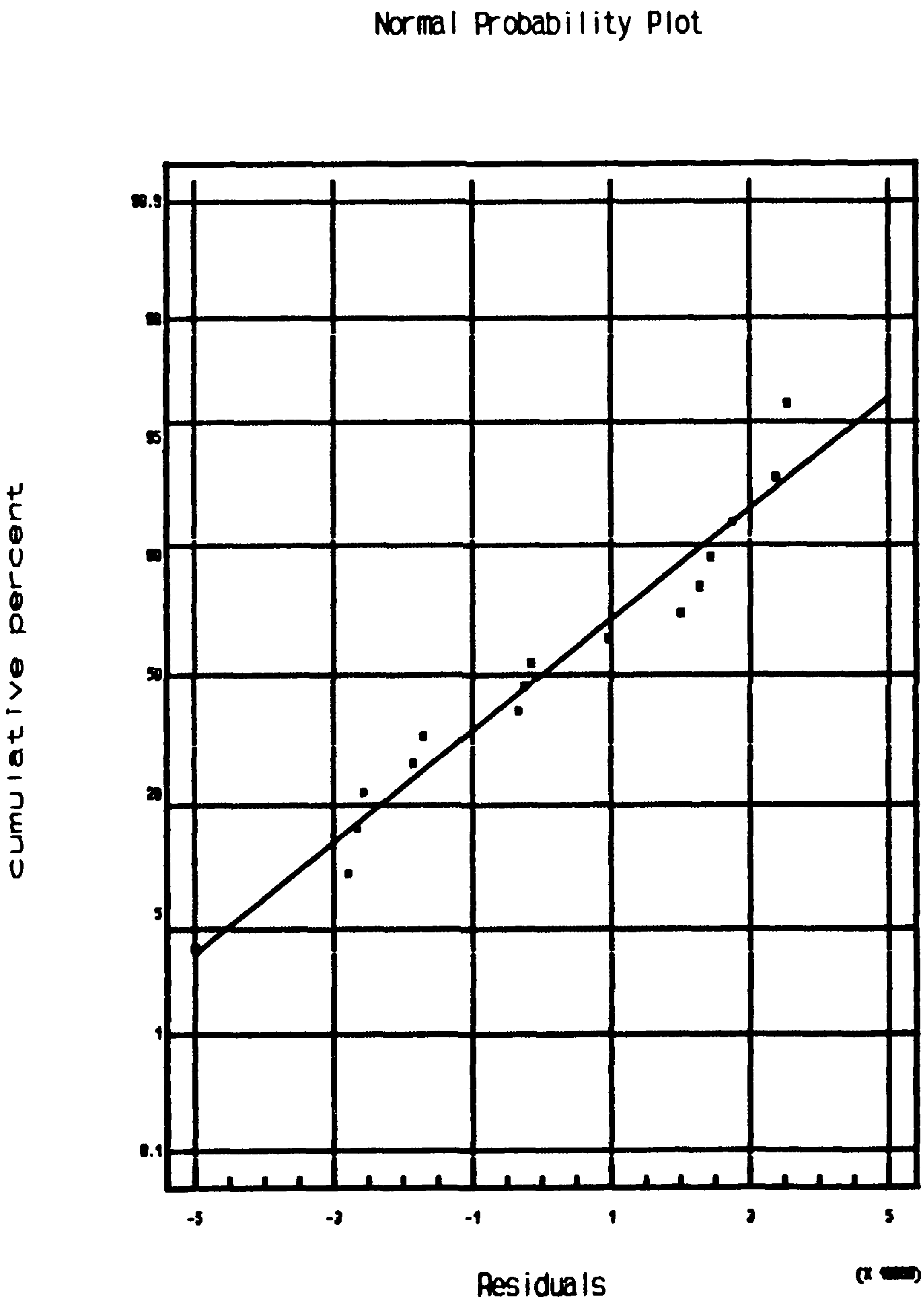

Figure 17. Normality Plot for Delinquent Tons, Factor Screen

Appendix C

Second Order Model Data

Table 33. Second Order Model Output Data (1-4)

Run No.	On Time Tons	Late Ton Days	Air Tons Moved	Delinquent Tons
1	4.36057E+06	8.76029E+05	1.07943E+06	1.72032E+05
2	4.28345E+06	1.18995E+06	1.03565E+06	2.11445E+05
3	4.35572E+06	1.24184E+06	1.07846E+06	2.34255E+05
4	4.39257E+06	6.65535E+05	8.89161E+05	1.58284E+05
5	4.42021E+06	7.08115E+05	9.20563E+05	1.82205E+05
6	4.44115E+06	6.22529E+05	9.25327E+05	1.59001E+05
7	4.50957E+06	6.02156E+05	9.63345E+05	1.58694E+05
8	4.17201E+06	1.35535E+06	9.08065E+05	2.53017E+05
9	4.15966E+06	1.28833E+06	8.23384E+05	2.63732E+05
10	4.45056E+06	5.31126E+05	9.23386E+05	1.48529E+05
11	4.18627E+06	1.21050E+06	8.65284E+05	2.25999E+05
12	4.18533E+06	1.17366E+06	9.09006E+05	2.18428E+05
13	4.38493E+06	5.05008E+05	8.83457E+05	1.34730E+05
14	4.17677E+06	1.29043E+06	8.16709E+05	2.51661E+05
15	4.16251E+06	1.23160E+06	8.71899E+05	2.33416E+05
16	4.17677E+06	1.19627E+06	8.18650E+05	2.39361E+05
17	4.40398E+06	4.34262E+05	9.12948E+05	1.30839E+05
18	4.53348E+06	6.47095E+05	9.94807E+05	1.65653E+05
19	4.56488E+06	7.09649E+05	1.08804E+06	1.89244E+05
20	4.28151E+06	1.20871E+06	1.02706E+06	2.08529E+05
21	4.56676E+06	3.73588E+05	1.09854E+06	1.27764E+05
22	4.55538E+06	3.65288E+05	1.04050E+06	1.28573E+05
23	4.20820E+06	1.09751E+06	9.82308E+05	1.98260E+05
24	4.55726E+06	3.65355E+05	1.05476E+06	1.28419E+05
25	4.22155E+06	1.11376E+06	9.72841E+05	2.06671E+05
26	4.56676E+06	5.06330E+05	1.09757E+06	1.48123E+05
27	4.15010E+06	1.39398E+06	6.92069E+05	3.32739E+05
28	4.43612E+06	5.21143E+05	9.80487E+05	1.33080E+05
29	4.32383E+06	5.75753E+05	9.22415E+05	1.44396E+05
30	4.43421E+06	5.52444E+05	9.80487E+05	1.35214E+05
31	4.33338E+06	5.84417E+05	9.26238E+05	1.45430E+05
32	4.45514E+06	4.68464E+05	1.00424E+06	1.33704E+05
33	4.28951E+06	5.39771E+05	9.05303E+05	1.40486E+05
34	4.43803E+06	4.42847E+05	9.82398E+05	1.29225E+05
35	4.31527E+06	5.12741E+05	9.22415E+05	1.38798E+05
36	4.45232E+06	4.25980E+05	1.00333E+06	1.28906E+05
37	4.31615E+06	5.45602E+05	8.97657E+05	1.42040E+05
38	4.44088E+06	4.41753E+05	9.84280E+05	1.29225E+05
39	4.30004E+06	5.28868E+05	9.17652E+05	1.40039E+05
40	4.51630E+06	3.82297E+05	9.77665E+05	1.29537E+05
41	4.18915E+06	1.14539E+06	9.27119E+05	2.08405E+05
42	4.35714E+06	4.80322E+05	9.50025E+05	1.33821E+05

Table 34. Second Order Model Output Data (5-8)

On Time Tons of:

Run No.	SWA Armor	SWA Infantry	SWA Combat Support	SWA Combat Services Support
1	85758.0	8741.6	66132.2	2.48387E+05
2	85758.0	7552.8	61509.3	2.45433E+05
3	85758.0	7203.1	61766.2	2.47205E+05
4	85758.0	19091.7	78331.3	2.65222E+05
5	85758.0	19091.7	78588.1	2.70833E+05
6	85758.0	19091.7	78588.1	2.72310E+05
7	85758.0	19091.7	78588.1	2.69947E+05
8	85758.0	0.0	61124.1	2.48387E+05
9	85758.0	0.0	61124.1	2.51340E+05
10	85758.0	19091.7	78331.3	2.64926E+05
11	85758.0	0.0	61124.1	2.48387E+05
12	85758.0	0.0	61124.1	2.51045E+05
13	85758.0	19091.7	73194.8	2.64336E+05
14	85758.0	0.0	61124.1	2.51340E+05
15	85758.0	0.0	61124.1	2.51045E+05
16	85758.0	0.0	61124.1	2.51340E+05
17	85758.0	19091.7	73194.8	2.66403E+05
18	85758.0	19091.7	79230.2	2.74377E+05
19	85758.0	19091.7	87705.4	2.73787E+05
20	85758.0	5175.0	61509.3	2.48387E+05
21	85758.0	19091.7	79487.0	2.74082E+05
22	85758.0	19091.7	87705.4	2.73787E+05
23	85758.0	1748.3	61124.1	2.48387E+05
24	85758.0	19091.7	87705.4	2.73787E+05
25	85758.0	3496.6	61509.3	2.50159E+05
26	85758.0	19091.7	79487.0	2.74082E+05
27	85758.0	0.0	61124.1	2.49568E+05
28	85758.0	19091.7	70241.4	2.63745E+05
29	85758.0	16294.4	70241.4	2.61382E+05
30	85758.0	19091.7	69599.3	2.63745E+05
31	85758.0	17063.7	71397.1	2.60496E+05
32	85758.0	19091.7	70498.2	2.64336E+05
33	85758.0	16224.5	64462.8	2.58133E+05
34	85758.0	19091.7	70369.8	2.64040E+05
35	85758.0	16224.5	70113.0	2.61382E+05
36	85758.0	19091.7	71268.7	2.65517E+05
37	85758.0	13846.7	69085.7	2.61087E+05
38	85758.0	19091.7	70498.2	2.64040E+05
39	85758.0	15804.9	69342.5	2.60496E+05
40	85758.0	19091.7	79230.2	2.74377E+05
41	85758.0	489.5	61124.1	2.51045E+05
42	85758.0	18182.6	67801.5	2.62563E+05

Table 35. Second Order Model Output Data (9-12)

On Time Tons of:

RUN No.	SWA Resupply	SWA Ammunition	NATO Armor	NATO Infantry
1	1.13388E+06	7314.0	3.14061E+05	1.72422E+05
2	1.13269E+06	7314.0	3.01100E+05	1.71732E+05
3	1.13269E+06	7314.0	3.26358E+05	1.72422E+05
4	1.15884E+06	7314.0	2.93124E+05	1.72250E+05
5	1.16479E+06	7314.0	2.89800E+05	1.68111E+05
6	1.16597E+06	7314.0	3.02097E+05	1.72077E+05
7	1.16360E+06	7314.0	3.24364E+05	1.72422E+05
8	1.10655E+06	7314.0	2.82489E+05	1.60008E+05
9	1.10655E+06	7314.0	2.87142E+05	1.61732E+05
10	1.15765E+06	7314.0	3.00103E+05	1.72422E+05
11	1.10655E+06	7314.0	3.00768E+05	1.67422E+05
12	1.10655E+06	7314.0	2.95450E+05	1.66215E+05
13	1.15765E+06	7314.0	2.94786E+05	1.72077E+05
14	1.10655E+06	7314.0	3.01765E+05	1.66560E+05
15	1.10655E+06	7314.0	2.87474E+05	1.66904E+05
16	1.10655E+06	7314.0	2.98109E+05	1.66215E+05
17	1.16122E+06	7314.0	2.88471E+05	1.68629E+05
18	1.18261E+06	7314.0	3.27355E+05	1.72422E+05
19	1.18024E+06	7314.0	3.28684E+05	1.72422E+05
20	1.13032E+06	7314.0	3.00435E+05	1.72422E+05
21	1.18380E+06	7314.0	3.28684E+05	1.72422E+05
22	1.18143E+06	7314.0	3.29349E+05	1.72422E+05
23	1.11606E+06	7314.0	2.76175E+05	1.62422E+05
24	1.17905E+06	7314.0	3.27023E+05	1.72422E+05
25	1.11962E+06	7314.0	2.94786E+05	1.72250E+05
26	1.18380E+06	7314.0	3.28684E+05	1.72422E+05
27	1.10179E+06	7314.0	2.94453E+05	1.62594E+05
28	1.15647E+06	7314.0	3.19379E+05	1.72422E+05
29	1.15647E+06	7314.0	2.90797E+05	1.62422E+05
30	1.15647E+06	7314.0	3.21040E+05	1.72422E+05
31	1.15884E+06	7314.0	2.90133E+05	1.69318E+05
32	1.15765E+06	7314.0	3.21373E+05	1.72422E+05
33	1.14696E+06	7314.0	2.85812E+05	1.66560E+05
34	1.15647E+06	7314.0	3.19379E+05	1.72422E+05
35	1.15647E+06	7314.0	2.88803E+05	1.62939E+05
36	1.15765E+06	7314.0	3.18049E+05	1.72422E+05
37	1.15171E+06	7314.0	2.98441E+05	1.70698E+05
38	1.15647E+06	7314.0	3.18714E+05	1.72422E+05
39	1.15647E+06	7314.0	2.80163E+05	1.59318E+05
40	1.17073E+06	7314.0	3.24364E+05	1.72422E+05
41	1.10774E+06	7314.0	2.89468E+05	1.65008E+05
42	1.15171E+06	7314.0	2.90797E+05	1.67422E+05

Table 36. Second Order Model Output Data (13-16)

On Time Tons of:

Run No.	NATO Combat Support	NATO Combat Services Support	NATO Resupply	NATO Ammunition
1	1.46253E+05	3.66194E+05	1.54037E+06	78102.0
2	1.41262E+05	3.40390E+05	1.53881E+06	78102.0
3	1.47252E+05	3.66194E+05	1.53726E+06	78102.0
4	1.39431E+05	3.27488E+05	1.53881E+06	78102.0
5	1.40097E+05	3.38493E+05	1.54037E+06	78102.0
6	1.41761E+05	3.38113E+05	1.54037E+06	78102.0
7	1.47418E+05	3.65435E+05	1.54037E+06	78102.0
8	1.38932E+05	3.18760E+05	1.54037E+06	78102.0
9	1.39431E+05	3.14586E+05	1.53570E+06	78102.0
10	1.44090E+05	3.52154E+05	1.54037E+06	78102.0
11	1.42593E+05	3.12309E+05	1.54037E+06	78102.0
12	1.36270E+05	3.18760E+05	1.53881E+06	78102.0
13	1.39598E+05	3.25211E+05	1.54037E+06	78102.0
14	1.38932E+05	3.12309E+05	1.54037E+06	78102.0
15	1.35438E+05	3.11929E+05	1.54037E+06	78102.0
16	1.38766E+05	3.10791E+05	1.54037E+06	78102.0
17	1.38267E+05	3.37354E+05	1.54037E+06	78102.0
18	1.47751E+05	3.66953E+05	1.53881E+06	78102.0
19	1.54406E+05	3.77199E+05	1.54037E+06	78102.0
20	1.41927E+05	3.44944E+05	1.54037E+06	78102.0
21	1.57734E+05	3.77958E+05	1.54037E+06	78102.0
22	1.50413E+05	3.74543E+05	1.53881E+06	78102.0
23	1.39265E+05	3.35077E+05	1.54037E+06	78102.0
24	1.53075E+05	3.75302E+05	1.54037E+06	78102.0
25	1.39598E+05	3.20278E+05	1.54037E+06	78102.0
26	1.57068E+05	3.79097E+05	1.54037E+06	78102.0
27	1.39431E+05	3.13447E+05	1.53259E+06	78102.0
28	1.46087E+05	3.54051E+05	1.54037E+06	78102.0
29	1.42926E+05	3.24452E+05	1.54037E+06	78102.0
30	1.46087E+05	3.54431E+05	1.54037E+06	78102.0
31	1.39099E+05	3.24452E+05	1.53881E+06	78102.0
32	1.47085E+05	3.64676E+05	1.54037E+06	78102.0
33	1.35937E+05	3.20278E+05	1.54037E+06	78102.0
34	1.46087E+05	3.54431E+05	1.54037E+06	78102.0
35	1.39598E+05	3.24452E+05	1.53881E+06	78102.0
36	1.46087E+05	3.62020E+05	1.54037E+06	78102.0
37	1.41594E+05	3.20278E+05	1.54037E+06	78102.0
38	1.46087E+05	3.57466E+05	1.54037E+06	78102.0
39	1.38267E+05	3.21796E+05	1.53881E+06	78102.0
40	1.47085E+05	3.61261E+05	1.54037E+06	78102.0
41	1.39265E+05	3.22175E+05	1.53726E+06	78102.0
42	1.41594E+05	3.39252E+05	1.54037E+06	78102.0

Table 37. Second Order Model Small Composite Design

Run No.	C-141	C-5	C-17	KC-10	CRAF WB	NB CRAF	WARNING TIME
1	1	-1	1	1	1	1	-1
2	1	1	-1	1	1	1	-1
3	-1	1	1	1	1	1	-1
4	-1	-1	-1	1	-1	1	1
5	-1	-1	-1	1	1	-1	1
6	-1	-1	-1	-1	1	1	1
7	1	1	1	-1	-1	-1	1
8	1	1	1	-1	-1	-1	1
9	1	1	1	-1	-1	-1	-1
10	-1	1	-1	-1	-1	1	-1
11	-1	-1	1	1	-1	-1	1
12	1	-1	-1	-1	1	-1	-1
13	-1	-1	1	-1	1	-1	-1
14	1	-1	-1	-1	-1	1	1
15	-1	1	-1	1	-1	-1	-1
16	-1	-1	1	-1	-1	1	-1
17	1	-1	-1	1	-1	-1	-1
18	-1	1	-1	-1	1	-1	1
19	1	1	-1	1	-1	1	1
20	-1	1	1	1	1	-1	1
21	1	-1	1	-1	1	1	-1
22	1	-1	1	1	1	-1	1
23	1	1	-1	-1	1	1	1
24	-1	1	1	1	-1	1	-1
25	1	-1	1	1	-1	1	1
26	1	1	-1	1	1	-1	-1
27	-1	1	1	-1	1	1	1
28	-1	-1	-1	-1	-1	-1	-1
29	1	0	0	0	0	0	0
30	-1	0	0	0	0	0	0
31	0	1	0	0	0	0	0
32	0	-1	0	0	0	0	0
33	0	0	1	0	0	0	0
34	0	0	-1	0	0	0	0
35	0	0	0	1	0	0	0
36	0	0	0	-1	0	0	0
37	0	0	0	0	1	0	0
38	0	0	0	0	-1	0	0
39	0	0	0	0	0	1	0
40	0	0	0	0	0	-1	0
41	0	0	0	0	0	0	1
42	0	0	0	0	0	0	-1
43	0	0	0	0	0	0	0

Table 38. Second Order Model for On Time Tons

LEAST SQUARES LINEAR REGRESSION OF ON TIME TONS

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	4.3763E+06	1.0284E+04	425.56	0.0000	
WARNING	1.3614E+05	6921.6	19.67	0.0000	.7327
C-141	2.5114E+04	6921.6	3.63	0.0010	.7547
C-5	1.9525E+04	6921.6	2.82	0.0080	.7680
C-17	3.7034E+04	6921.6	5.35	0.0000	.8338
KC-10	2.4744E+04	6921.6	3.57	0.0011	.8512
WB CRAF	3.3509E+04	6921.6	4.84	0.0000	.8949
NB CRAF	2.3640E+04	6921.6	3.42	0.0017	.9177
$WARNING^2$	-2.2194E+04	12396	-1.79	0.0826	.9227

CASES INCLUDED	42	MISSING CASES	0
DEGREES OF FREEDOM	33		
OVERALL F	62.17	P VALUE	0.0000
ADJUSTED R SQUARED	0.9227		
R SQUARED	0.9378		
RESID. MEAN SQUARE	1.375E+09		

Table 39. Second Order Model for Late Ton Days

LEAST SQUARES LINEAR REGRESSION OF LATE TON DAYS

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	4.9536E+05	2.5891E+04	19.13	0.0000	
WARNING	-3.3571E+05	1.6688E+04	-20.12	0.0000	.6678
C-141	-4.7222E+04	1.6688E+04	-2.83	0.0078	.6764
C-17	-3.0189E+04	1.6688E+04	-1.81	0.0793	.6766
WB CRAF	-3.5966E+04	1.6688E+04	-2.16	0.0383	.6738
NB CRAF	-2.9755E+04	1.6688E+04	-1.78	0.0835	.6689
$WARNING^2$	2.8562E+05	4.7507E+04	6.01	0.0000	.9284
$C-5^2$	9.0212E+04	4.7507E+04	1.90	0.0661	.9334

CASES INCLUDED	42	MISSING CASES	0
DEGREES OF FREEDOM	34		
OVERALL F	83.06	P VALUE	0.0000
ADJUSTED R SQUARED	0.9334		
R SQUARED	0.9448		
RESID. MEAN SQUARE	8.020E+09		

Table 40. Second Order Model For Air Tons Moved

LEAST SQUARES LINEAR REGRESSION OF AIR TONS MOVED

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	9.5183E+05	842.39	1129.92	0.0000	
C-141	2.8114E+04	1015.1	27.69	0.0000	.0552
C-5	2.6136E+04	1015.1	25.75	0.0000	.1073
C-17	5.2109E+04	1015.1	51.33	0.0000	.4048
KC-10	3.0653E+04	1015.1	30.20	0.0000	.4763
WB CRAF	5.2037E+04	1015.1	51.26	0.0000	.7569
NB CRAF	3.2905E+04	1015.1	32.41	0.0000	.8859
WARNING	3.1198E+04	1015.1	30.73	0.0000	.9959

CASES INCLUDED	42	MISSING CASES	0
DEGREES OF FREEDOM	34		
OVERALL F	1.430E+03	P VALUE	0.0000
ADJUSTED R SQUARED	0.9959		
R SQUARED	0.9966		
RESID. MEAN SQUARE	2.959E+07		

Table 41. Second Order Model For Delinquent Tons

LEAST SQUARES LINEAR REGRESSION OF DELINQUENT TONS

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	1.3649E+05	5513.4	24.76	0.0000	
WARNING	-4.0655E+04	3704.2	-10.98	0.0000	.4803
C-141	-1.1681E+04	3704.2	-3.15	0.0033	.5160
C-17	-7675.1	3704.2	-2.07	0.0457	.5286
WB CRAF	-9507.8	3704.2	-2.57	0.0147	.5390
NB CRAF	-9341.0	3704.2	-2.52	0.0164	.5504
$WARNING^2$	5.3386E+04	6642.2	8.04	0.0000	.8377

CASES INCLUDED	42	MISSING CASES	0
DEGREES OF FREEDOM	35		
OVERALL F	36.26	P VALUE	0.0000
ADJUSTED R SQUARED	0.8377		
R SQUARED	0.8614		
RESID. MEAN SQUARE	3.952E+08		

Table 42. Second Order Model for First Principal Component

LEAST SQUARES LINEAR REGRESSION OF PRINCIPAL COMPONENT 1
(FORMED FROM ON TIME TONS, AIR TONS, AND DELINQUENT TONS)

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	T TEST	P	ADJUSTED R-SQUARED
CONSTANT	-5.2602E-01	6.0868E-02	-8.64	0.0000	
C-141	-4.2843E-01	4.0969E-02	-10.46	0.0000	.0282
C-5	-2.5195E-01	4.0969E-02	-6.15	0.0000	.0223
C-17	-5.9164E-01	4.0969E-02	-14.44	0.0000	.1176
KC-10	-3.6772E-01	4.0969E-02	-8.98	0.0000	.1402
WB CRAF	-6.0132E-01	4.0969E-02	-14.68	0.0000	.2541
NB CRAF	-4.3082E-01	4.0969E-02	-10.52	0.0000	.3144
WARNING	-1.2930	4.0969E-02	-31.56	0.0000	.9198
$WARNING^2$	7.2164E-01	7.3371E-02	9.84	0.0000	.9790

CASES INCLUDED	42	MISSING CASES	0
DEGREES OF FREEDOM	33		
OVERALL F	239.7	P VALUE	0.0000
ADJUSTED R SQUARED	0.9790		
R SQUARED	0.9831		
RESID. MEAN SQUARE	4.816E-02		

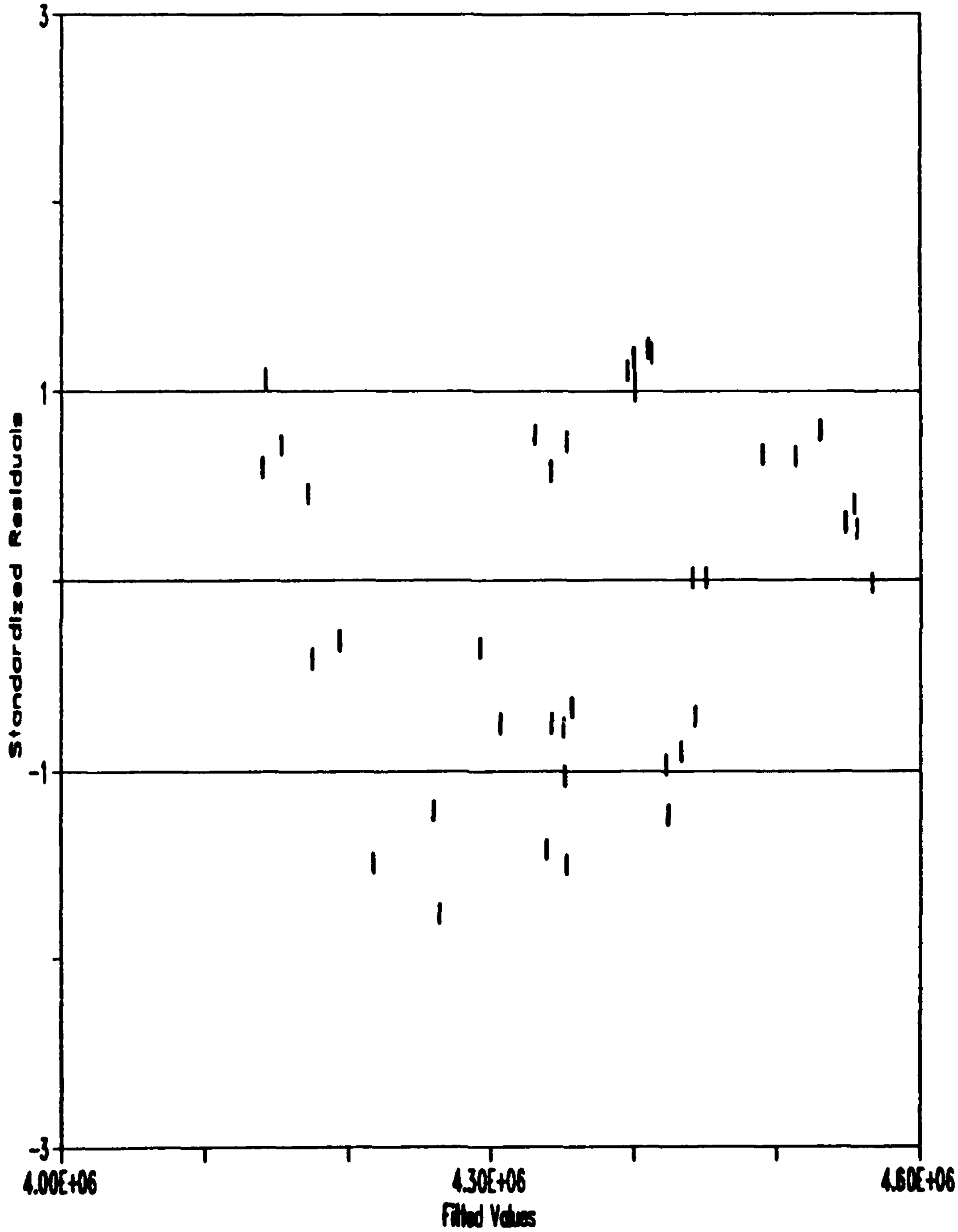

Figure 18. Standardized Residuals for On Time Tons, Second Order

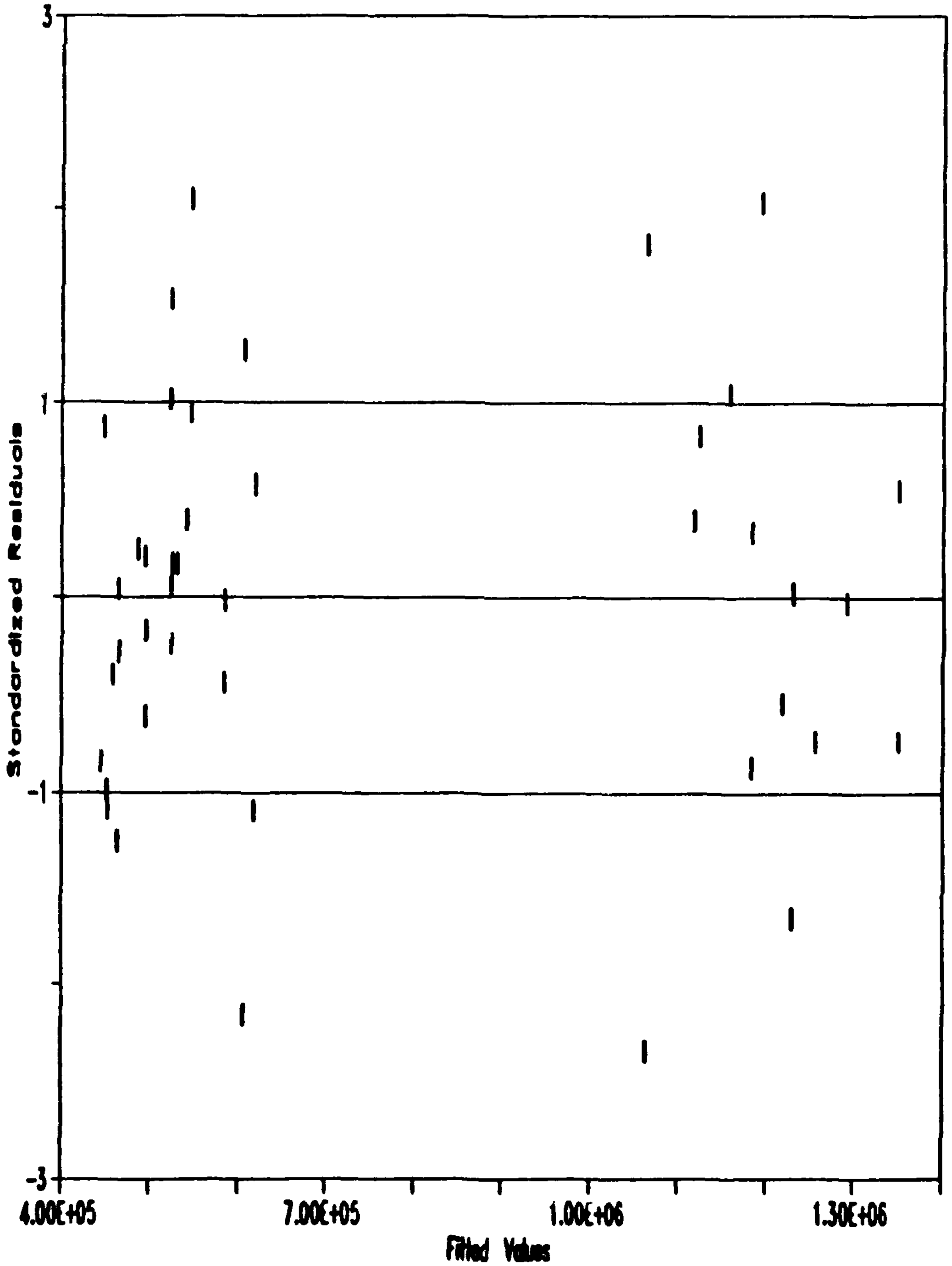

Figure 19. Standardized Residuals for Late Ton Days, Second Order

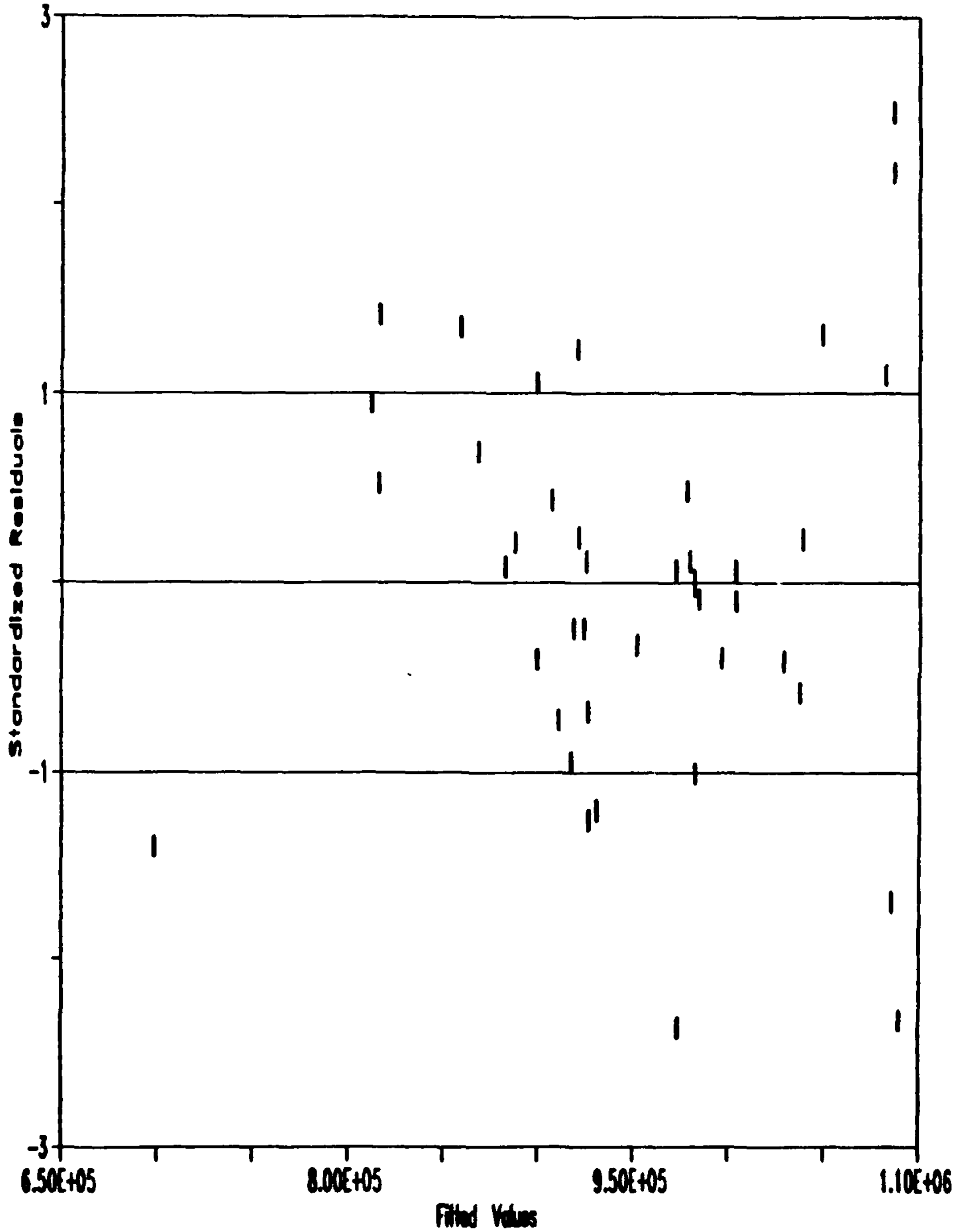

Figure 20. Standardized Residuals for Air Tons Moved, Second Order

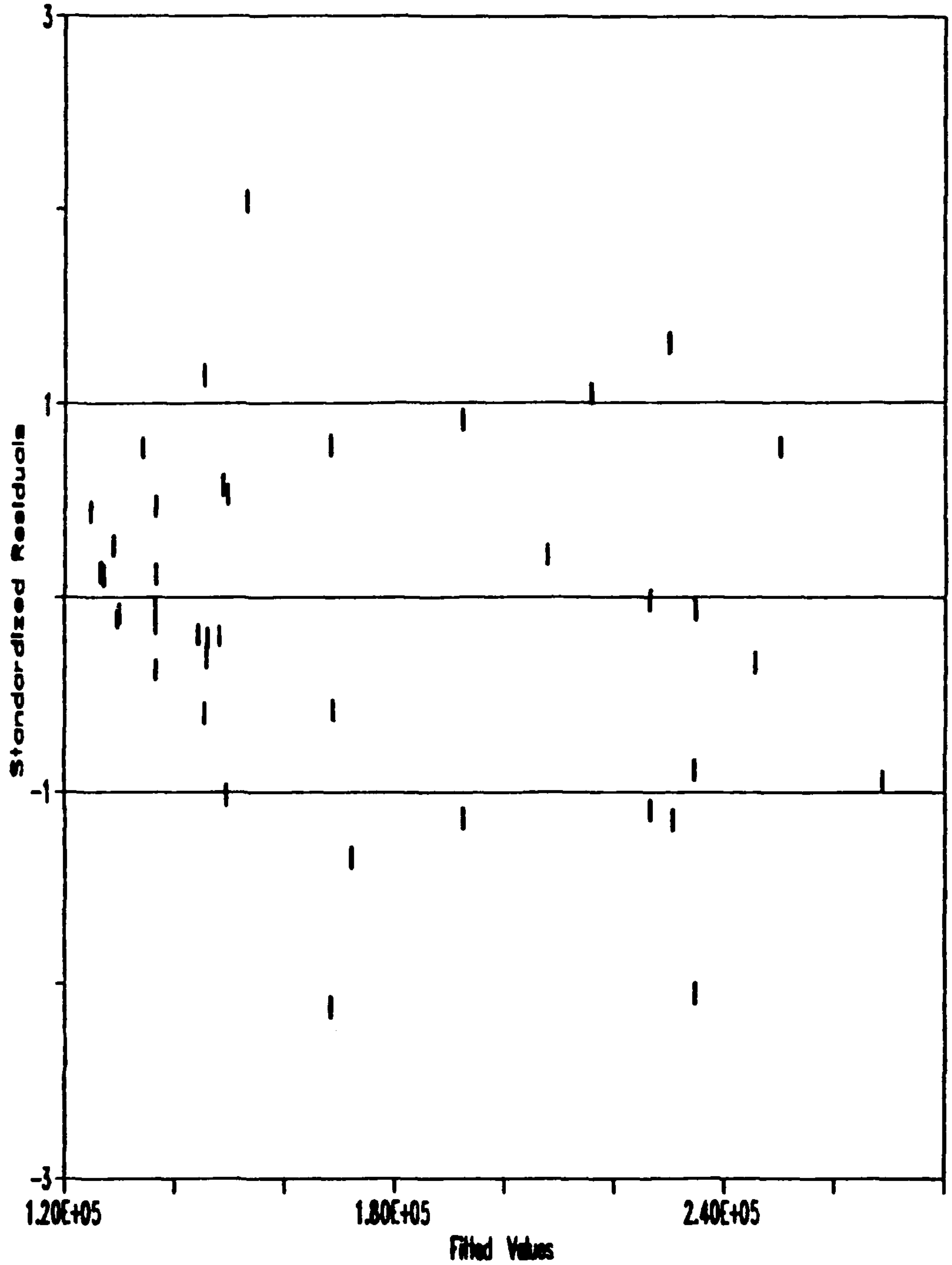

Figure 21. Standardized Residuals for Delinquent Tons, Second Order

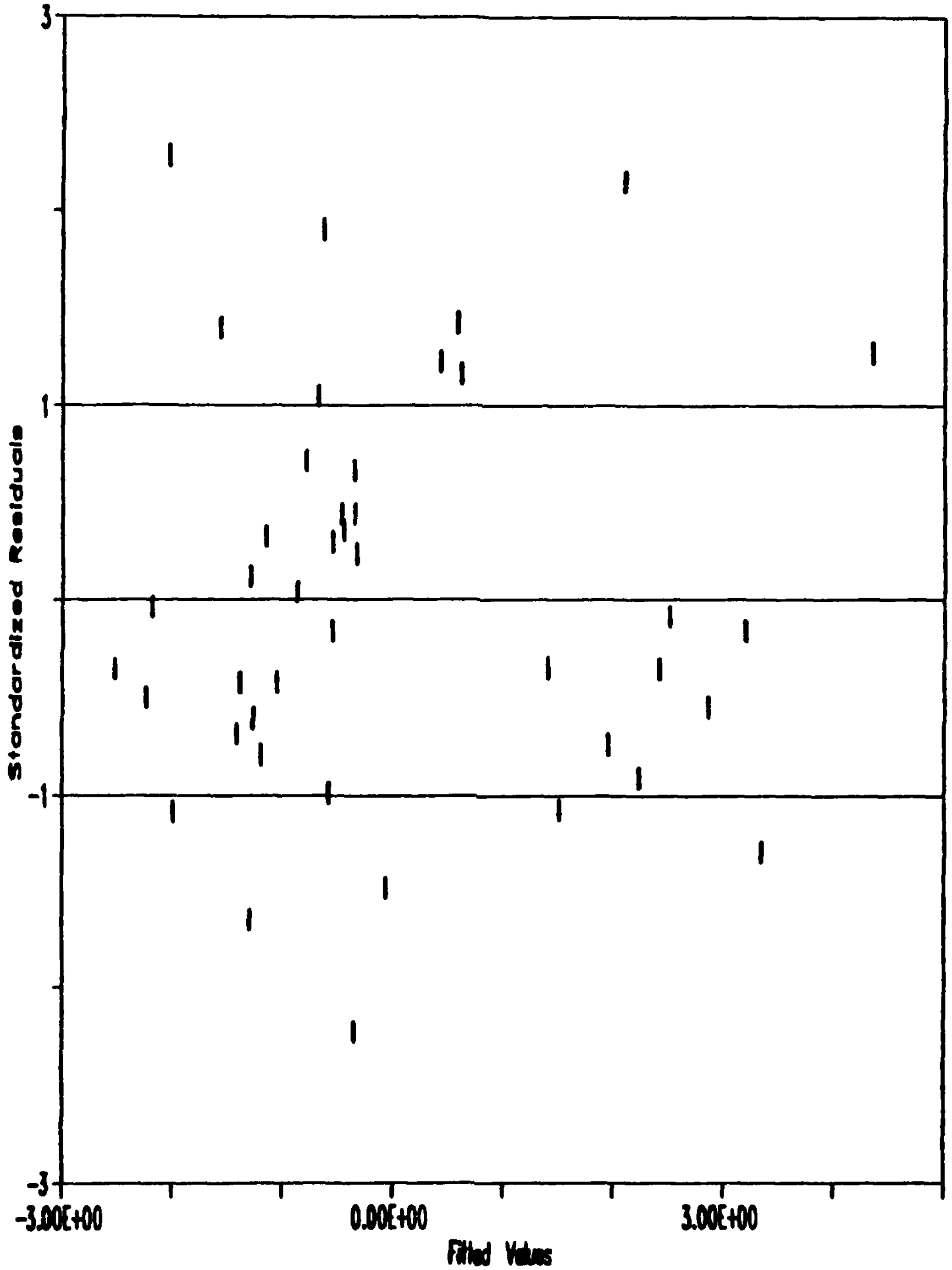

Figure 22. Standardized Residuals for First Principal Component, Second Order

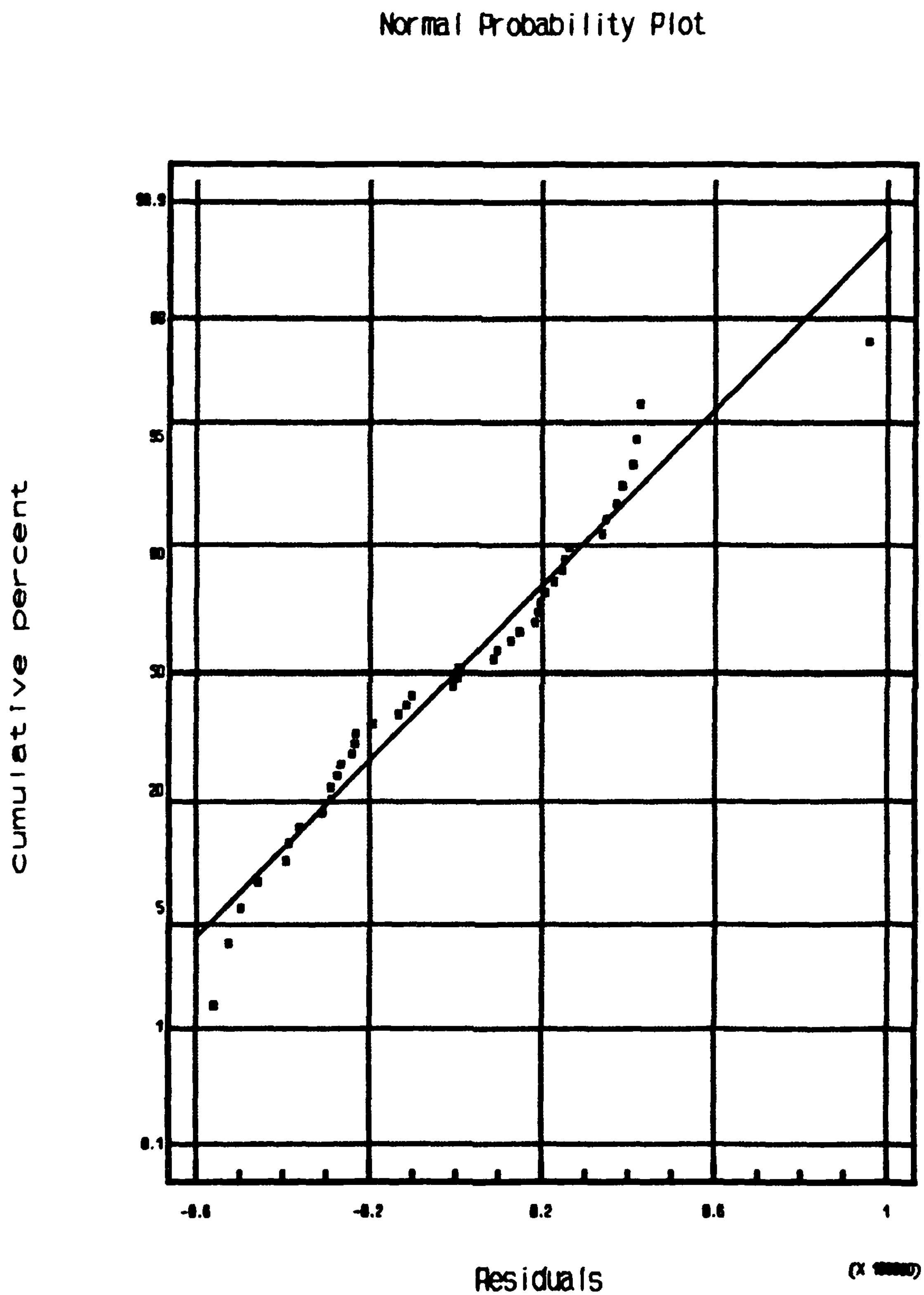

Figure 23. Normality Plot of On Time Tons Residuals Second order (Wilks-Shapiro = .9490)

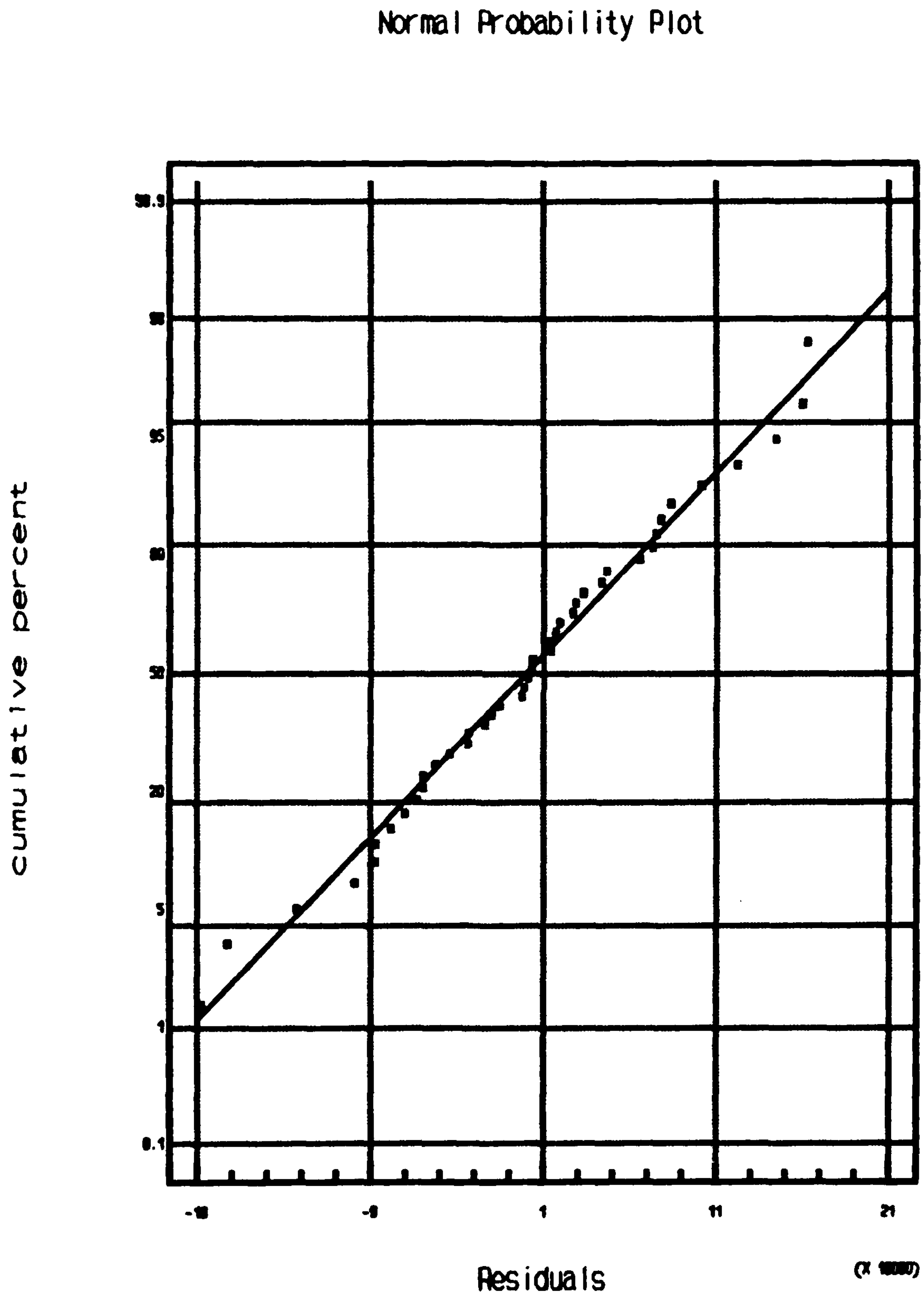

Figure 24. Normality Plot of Residuals for Late Ton Days Second Order (Wilks-Shapiro = .9896)

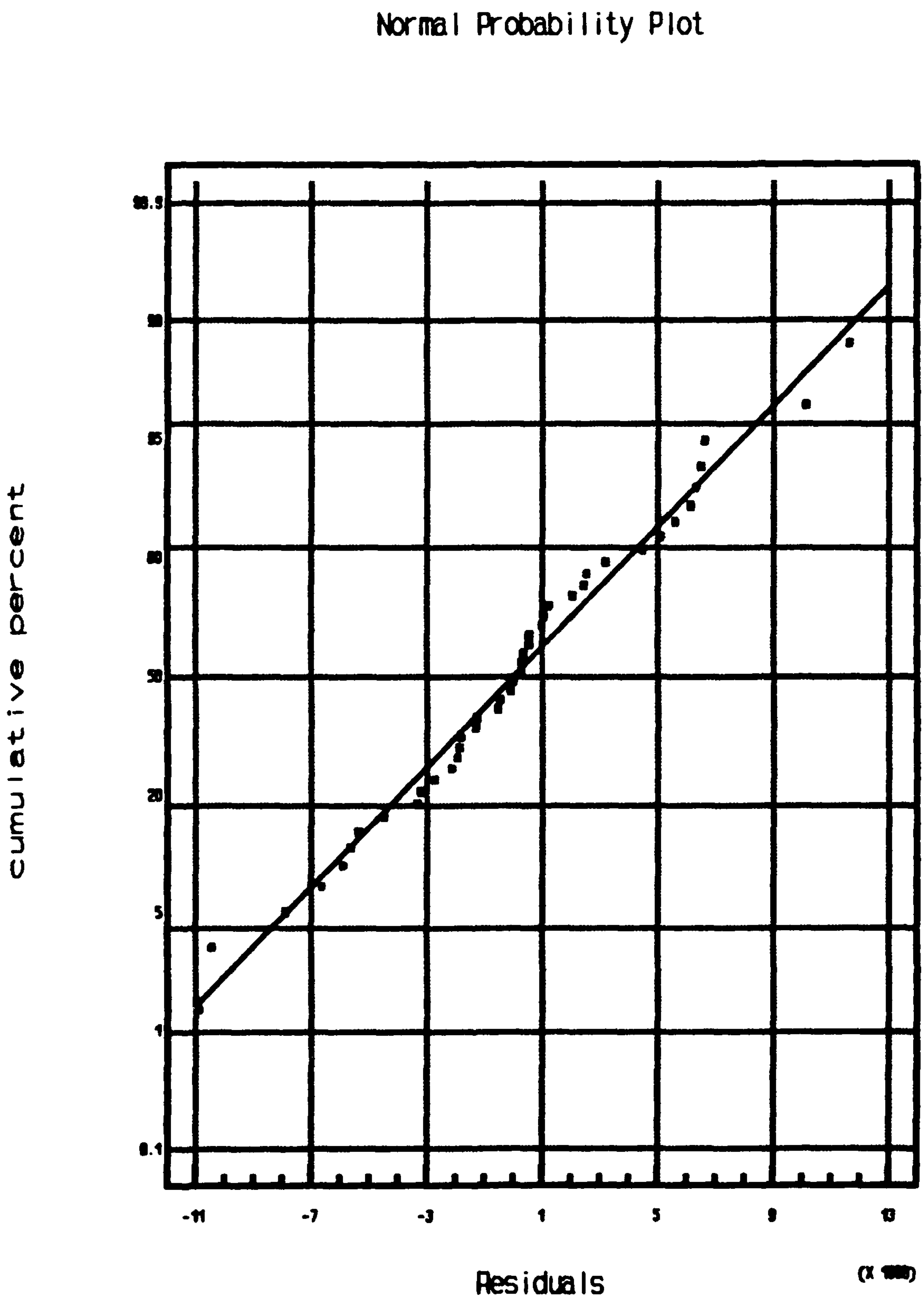

Figure 25. Normality Plot of Residuals for Air Tons Moved Second Order (Wilks-Shapiro = .9317)

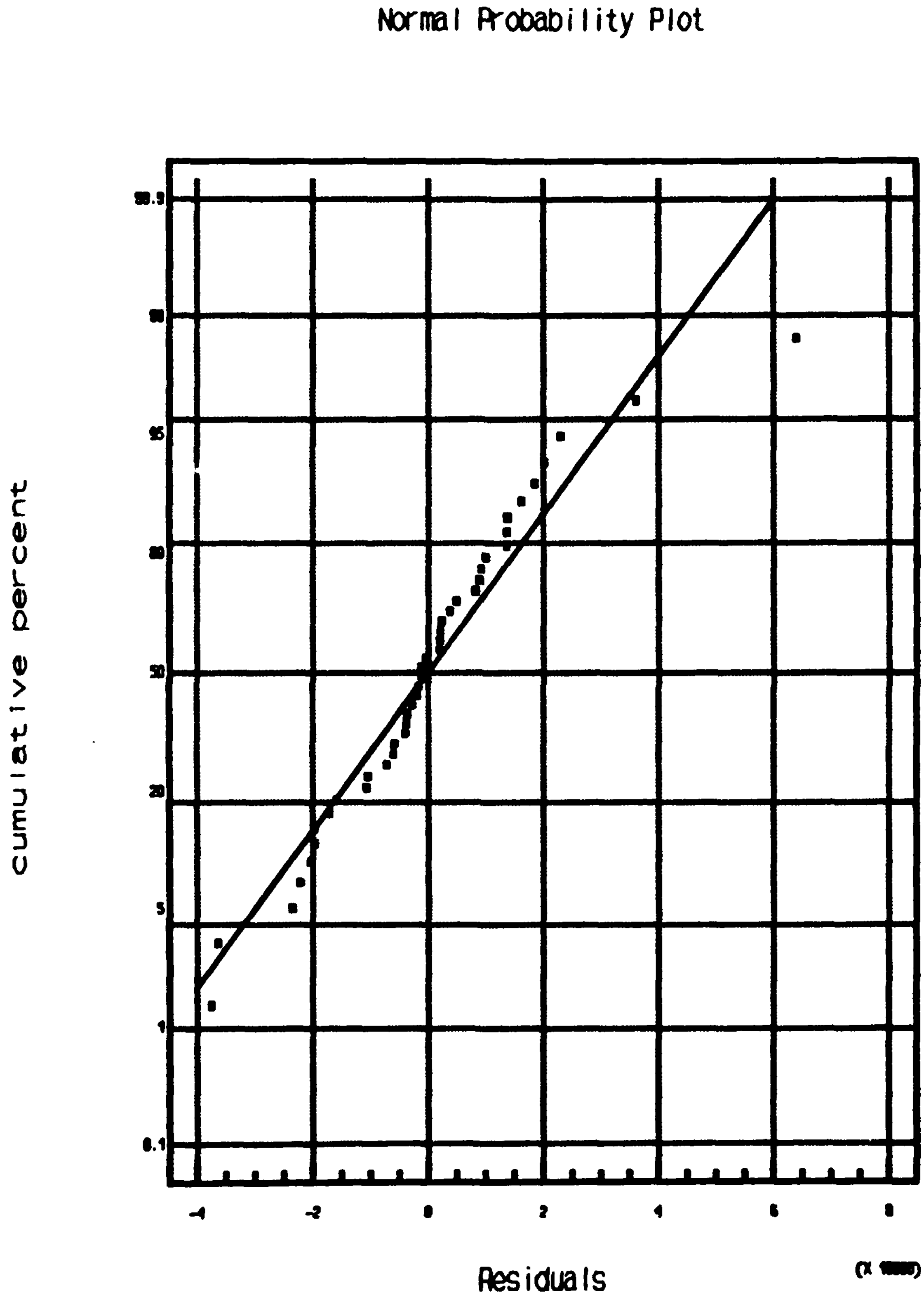

Figure 26. Normality Plot for Delinquent Tons Second Order (Wilks-Shapiro = .9850)

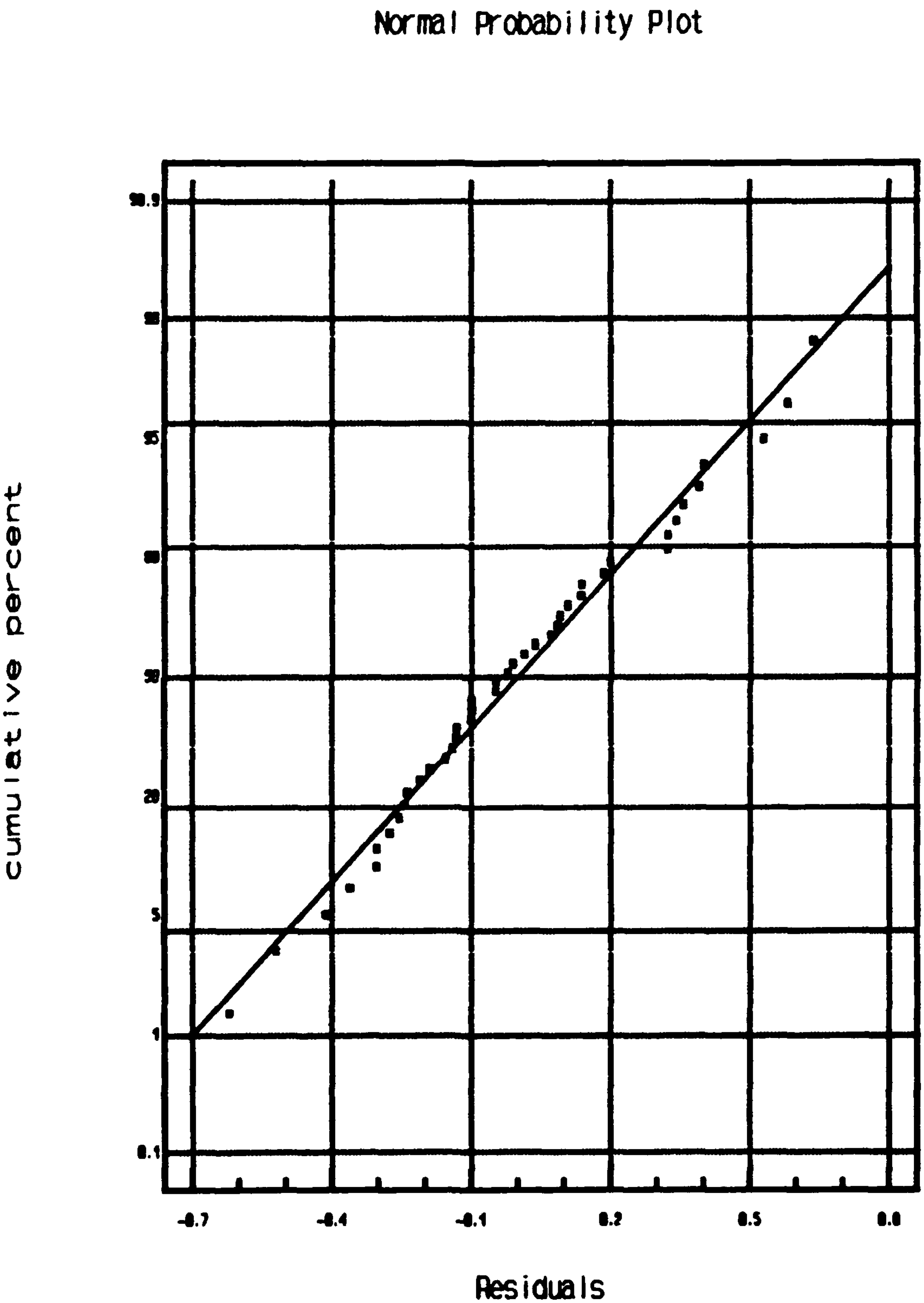

Figure 27. **Normality Plot for Residuals for First Principal Component, Second Order**

Table 43. Second Order Model Validation Design Points

Aircraft (Number)	Validation Coded Values Run			Validation Raw Values Run		
	1	2	3	1	2	3
C-17	0.50000	-0.50000	0.16667	195	165	185
C-141	-0.45946	0.35135	-0.18919	180	210	190
C-5	-0.69231	0.53846	0.00000	88	104	97
KC-10	0.50000	-0.50000	0.00000	50	30	40
WB CRAF	-0.40000	0.60000	0.20000	115	140	130
NB CRAF	-0.42857	0.28571	-0.14286	70	95	80
WB PAX	0.00000	0.00000	0.00000	310	310	310
Warning Time (Days)	-0.66667	-0.33333	0.33333	5	6	8
	4	5	6	4	5	6
C-17	-0.50000	-0.50000	-0.50000	165	165	165
C-141	-0.59459	-0.59459	-0.59459	175	175	175
C-5	-0.53846	-0.53846	-0.53846	90	90	90
KC-10	0.00000	0.00000	0.00000	40	40	40
WB CRAF	-0.40000	-0.40000	-0.40000	115	115	115
NB CRAF	-0.57143	-0.57143	-0.57143	65	65	65
WB PAX	0.00000	0.00000	0.00000	310	310	310
Warning Time (Days)	-0.33333	0.33333	0.00000	6	8	7
	7	8	9	7	8	9
C-17	0.50000	0.50000	0.50000	195	195	195
C-141	0.62162	0.62162	0.62162	220	220	220
C-5	0.61538	0.61538	0.61538	105	105	105
KC-10	0.50000	0.50000	0.50000	50	50	50
WB CRAF	0.40000	0.40000	0.40000	135	135	135
NB CRAF	0.57143	0.57143	0.57143	105	105	105
WB PAX	0.00000	0.00000	0.00000	310	310	310
Warning Time (Days)	-0.33333	0.33333	0.00000	6	8	7

Appendix D

Aircraft / Ship Data

Table 44. Aircraft / Ship Effects Output Data (1-4)

Run No.	On Time Tons	Late Ton Days	Air Tons Moved	Delinquent Tons
1	3.1766E+06	7.1323E+06	4.3272E+05	8.4976E+05
2	3.4492E+06	5.5389E+06	4.4083E+05	8.1746E+05
3	3.9834E+06	1.7103E+06	4.8115E+05	4.8899E+05
4	4.1263E+06	1.6141E+06	4.7070E+05	4.2420E+05
5	4.1597E+06	1.7309E+06	4.6620E+05	4.2310E+05
6	4.1745E+06	1.7720E+06	4.7850E+05	3.5621E+05
7	4.1714E+06	1.5991E+06	4.8172E+05	3.1583E+05
8	3.1502E+06	6.8469E+06	4.7457E+05	8.9851E+05
9	3.2745E+06	4.4434E+06	6.2486E+05	5.8414E+05
10	4.0161E+06	1.3578E+06	5.2727E+05	4.4030E+05
11	4.1593E+06	1.3880E+06	5.1367E+05	3.8642E+05
12	4.1916E+06	1.5827E+06	5.1792E+05	4.0199E+05
13	4.1927E+06	1.6513E+06	5.2235E+05	3.2850E+05
14	4.1904E+06	1.4597E+06	5.2356E+05	2.9321E+05
15	3.1743E+06	7.0011E+06	5.2781E+05	9.2274E+05
16	3.4640E+06	5.0366E+06	5.3150E+05	6.8418E+05
17	4.0816E+06	1.2485E+06	5.7330E+05	4.0843E+05
18	4.1641E+06	1.2794E+06	5.8642E+05	3.6712E+05
19	4.1995E+06	1.6542E+06	5.6393E+05	4.0483E+05
20	4.2111E+06	1.5585E+06	5.6551E+05	3.1892E+05
21	4.1980E+06	1.3770E+06	5.7210E+05	2.8115E+05
22	3.1445E+06	6.8523E+06	5.7764E+05	9.0081E+05
23	3.5236E+06	4.2531E+06	5.9828E+05	6.1709E+05
24	4.1023E+06	1.1485E+06	6.3395E+05	3.6697E+05
25	4.1966E+06	1.1821E+06	6.3047E+05	3.4127E+05

Run No.	On Time Tons	Late Ton Days	Air Tons Moved	Delinquent Tons
26	4.2104E+06	1.4216E+06	6.0797E+05	3.5933E+05
27	4.2200E+06	1.4848E+06	6.1526E+05	2.9605E+05
28	4.2076E+06	1.3046E+06	6.1874E+05	2.4787E+05
29	3.2184E+06	6.3686E+06	6.2122E+05	8.7892E+05
30	3.2938E+06	4.4536E+06	6.2980E+05	5.9098E+05
31	4.1482E+06	1.0922E+06	6.7533E+05	3.4254E+05
32	4.2250E+06	1.1232E+06	6.6292E+05	3.1068E+05
33	3.9753E+06	1.5367E+06	4.0857E+05	4.8260E+05
34	4.2612E+06	1.3846E+06	6.6235E+05	2.3264E+05
35	4.2600E+06	1.1921E+06	6.6634E+05	1.9005E+05
36	3.3373E+06	5.7327E+06	6.6914E+05	7.8091E+05
37	3.5585E+06	4.1612E+06	6.8669E+05	5.3420E+05
38	4.1533E+06	9.6088E+05	7.1171E+05	2.8091E+05
39	4.2634E+06	8.8460E+05	7.0786E+05	2.3933E+05
40	4.2603E+06	8.7413E+05	7.0963E+05	2.3516E+05
41	4.2826E+06	7.3073E+05	7.1496E+05	1.4386E+05
42	4.2714E+06	5.2282E+05	7.1774E+05	1.0769E+05
43	3.2257E+06	6.2642E+06	7.0424E+05	9.2371E+05
44	3.6447E+06	3.8051E+06	7.2763E+05	5.2410E+05
45	4.2099E+06	9.5030E+05	7.5880E+05	2.7666E+05
46	4.2807E+06	9.8579E+05	7.5957E+05	2.4643E+05
47	4.2983E+06	1.2121E+06	7.6046E+05	2.6504E+05
48	4.3071E+06	1.2712E+06	7.6864E+05	1.8399E+05
49	4.2839E+06	1.1158E+06	7.7105E+05	1.4648E+05

Table 45. Aircraft / Ship Effects Output Data (5-8)

On Time Tons of:

Run No.	SWA Armor	SWA Infantry	SWA Combat Support	SWA Combat Services Support
1	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2	0.0000E+00	0.0000E+00	1.1904E+02	6.6984E+03
3	8.5243E+04	0.0000E+00	5.5089E+04	2.4012E+05
4	8.5758E+04	0.0000E+00	6.3307E+04	2.5931E+05
5	8.5758E+04	0.0000E+00	6.3564E+04	2.5518E+05
6	8.5758E+04	0.0000E+00	6.3564E+04	2.6522E+05
7	8.5758E+04	0.0000E+00	7.5249E+04	2.6552E+05
8	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
9	0.0000E+00	1.1259E+04	4.7674E+02	1.7059E+04
10	8.5758E+04	0.0000E+00	5.5089E+04	2.4396E+05
11	8.5758E+04	0.0000E+00	6.3692E+04	2.5164E+05
12	8.5758E+04	0.0000E+00	7.5249E+04	2.5577E+05
13	8.5758E+04	0.0000E+00	6.3564E+04	2.6522E+05
14	8.5758E+04	0.0000E+00	7.5249E+04	2.6552E+05
15	0.0000E+00	2.7274E+03	0.0000E+00	0.0000E+00
16	0.0000E+00	2.7274E+03	1.1909E+02	1.6610E+03
17	8.5758E+04	2.7274E+03	6.1381E+04	2.4839E+05
18	8.5758E+04	2.7274E+03	6.1381E+04	2.5134E+05
19	2.7274E+03	6.1381E+04	1.4903E+04	3.9034E+03
20	8.5758E+04	2.7274E+03	6.4078E+04	2.6611E+05
21	8.5758E+04	2.7274E+03	7.1911E+04	2.6611E+05
22	0.0000E+00	6.3639E+03	0.0000E+00	0.0000E+00
23	3.5221E+03	6.3639E+03	2.3837E+02	2.4554E+04
24	8.5758E+04	7.1332E+03	6.1381E+04	2.4602E+05
25	8.5758E+04	6.3639E+03	7.1012E+04	2.5400E+05

On Time Tons of:

Run No.	SWA Armor	SWA Infantry	SWA Combat Support	SWA Combat Services Support
26	8.5758E+04	6.3639E+03	6.6517E+04	2.5577E+05
27	8.5758E+04	6.3639E+03	7.4864E+04	2.6640E+05
28	8.5758E+04	6.3639E+03	7.4864E+04	2.6611E+05
29	0.0000E+00	1.0140E+04	0.0000E+00	0.0000E+00
30	0.0000E+00	1.0140E+04	4.7674E+02	1.6803E+04
31	8.5758E+04	1.0140E+04	6.1381E+04	2.4661E+05
32	8.5758E+04	1.0140E+04	6.1381E+04	2.4898E+05
33	8.5758E+04	1.9092E+04	7.3195E+04	2.6847E+05
34	8.5758E+04	1.0140E+04	7.1140E+04	2.7201E+05
35	8.5758E+04	1.0140E+04	7.3066E+04	2.7231E+05
36	0.0000E+00	1.3777E+04	0.0000E+00	0.0000E+00
37	3.5739E+03	1.3777E+04	2.3837E+02	1.8014E+04
38	8.5758E+04	1.3777E+04	6.1253E+04	2.4868E+05
39	8.5758E+04	1.3777E+04	7.5249E+04	2.5754E+05
40	8.5758E+04	1.3777E+04	6.6517E+04	2.5695E+05
41	8.5758E+04	1.3777E+04	7.3965E+04	2.7261E+05
42	8.5758E+04	1.3777E+04	6.7673E+04	2.7290E+05
43	0.0000E+00	1.7204E+04	0.0000E+00	0.0000E+00
44	9.6339E+03	1.7204E+04	1.0727E+04	4.3142E+04
45	8.5758E+04	1.7204E+04	6.5233E+04	2.5341E+05
46	8.5758E+04	1.7204E+04	6.5490E+04	2.5429E+05
47	8.5758E+04	1.7204E+04	7.0498E+04	2.5813E+05
48	8.5758E+04	1.7204E+04	7.7689E+04	2.7290E+05
49	8.5758E+04	1.7204E+04	6.9599E+04	2.7320E+05

Table 46. Aircraft / Ships Effects Output Data (9-12)

On Time Tons of:

RUN No.	SWA Resupply	SWA Ammunition	NATO Armor	NATO Infantry
1	5.8288E+05	10040.7	2.7152E+05	1.5915E+05
2	8.4447E+05	10247.0	2.7418E+05	1.5915E+05
3	9.9241E+05	7314.00	2.7518E+05	1.5915E+05
4	1.0856E+06	11863.2	2.7518E+05	1.5915E+05
5	1.1298E+06	11863.2	2.7518E+05	1.5915E+05
6	1.1369E+06	11863.2	2.7418E+05	1.5915E+05
7	1.1386E+06	7314.00	2.6155E+05	1.6449E+05
8	5.3281E+05	10040.7	2.6487E+05	1.5932E+05
9	8.4100E+05	8080.71	2.6853E+05	1.5915E+05
10	1.0002E+06	7314.00	2.7052E+05	1.6035E+05
11	1.1131E+06	11863.2	2.6886E+05	1.6035E+05
12	1.1298E+06	11863.2	2.7052E+05	1.6035E+05
13	1.1369E+06	11863.2	2.7052E+05	1.6035E+05
14	1.1386E+06	7314.00	2.7052E+05	1.6225E+05
15	5.6111E+05	6945.97	2.6055E+05	1.6001E+05
16	8.4553E+05	10247.0	2.6055E+05	1.6001E+05
17	1.0176E+06	11863.2	2.7883E+05	1.6087E+05
18	1.1107E+06	11863.2	2.7883E+05	1.6087E+05
19	0.0000E+00	11863.2	2.7883E+05	1.6087E+05
20	1.1358E+06	11863.2	2.7518E+05	1.6277E+05
21	1.1303E+06	7314.00	2.7883E+05	1.6277E+05
22	5.1734E+05	10040.7	2.5889E+05	1.5915E+05
23	8.4641E+05	10247.0	2.8216E+05	1.5535E+05
24	1.0320E+06	11863.2	2.7950E+05	1.5794E+05
25	1.1191E+06	11863.2	2.7950E+05	1.5794E+05

On Time Tons of:

RUN No.	SWA Resupply	SWA Ammunition	NATO Armor	NATO Infantry
26	1.1358E+06	11863.2	2.7950E+05	1.5794E+05
27	1.1250E+06	11863.2	2.8249E+05	1.5794E+05
28	1.1291E+06	7314.00	2.8482E+05	1.5794E+05
29	5.4877E+05	10040.7	2.9578E+05	1.5725E+05
30	8.4150E+05	10247.0	2.9578E+05	1.5725E+05
31	1.0320E+06	11863.2	3.0941E+05	1.5828E+05
32	1.1167E+06	11863.2	3.0642E+05	1.5828E+05
33	1.1620E+06	11863.2	2.7185E+05	1.5397E+05
34	1.1179E+06	11863.2	3.0442E+05	1.6104E+05
35	1.1279E+06	7314.00	3.0509E+05	1.6104E+05
36	6.7108E+05	6945.97	2.9312E+05	1.5690E+05
37	8.4794E+05	10247.0	2.9312E+05	1.5690E+05
38	1.0320E+06	11863.2	3.0176E+05	1.5604E+05
39	1.1274E+06	11863.2	3.0110E+05	1.5604E+05
40	1.1322E+06	11863.2	3.0575E+05	1.5604E+05
41	1.1226E+06	11863.2	2.9445E+05	1.6259E+05
42	1.1315E+06	7314.00	2.9645E+05	1.6259E+05
43	5.1287E+05	10040.7	2.9412E+05	1.6035E+05
44	8.5892E+05	11863.2	2.9412E+05	1.6035E+05
45	1.0534E+06	11863.2	3.0210E+05	1.5897E+05
46	1.1334E+06	11863.2	3.0210E+05	1.5897E+05
47	1.1417E+06	11863.2	2.9977E+05	1.5897E+05
48	1.1250E+06	11863.2	2.9611E+05	1.6121E+05
49	1.1351E+06	7314.00	2.8781E+05	1.6121E+05

Table 47. Aircraft / Ship Effects Output Data (13-16)

On Time Tons of:

Run No.	NATO Combat Support	NATO Combat Services Support	NATO Resupply	NATO Ammunition
1	1.3943E+05	2.8650E+05	1.5310E+06	78102.0
2	1.3793E+05	2.7246E+05	1.5341E+06	78102.0
3	1.3993E+05	2.8650E+05	1.5341E+06	78102.0
4	1.3993E+05	2.8650E+05	1.5341E+06	78102.0
5	1.3993E+05	2.8650E+05	1.5341E+06	78102.0
6	1.3993E+05	2.8650E+05	1.5341E+06	78102.0
7	1.4110E+05	2.8840E+05	1.5404E+06	78102.0
8	1.3927E+05	2.9599E+05	1.5404E+06	78102.0
9	1.4243E+05	2.9409E+05	1.2992E+06	78102.0
10	1.3877E+05	3.0092E+05	1.5404E+06	78102.0
11	1.3877E+05	3.0092E+05	1.5404E+06	78102.0
12	1.3877E+05	3.0092E+05	1.5404E+06	78102.0
13	1.3960E+05	3.0092E+05	1.5404E+06	78102.0
14	1.3960E+05	3.0092E+05	1.5404E+06	78102.0
15	1.3511E+05	2.9751E+05	1.5404E+06	78102.0
16	1.3461E+05	2.8233E+05	1.5404E+06	78102.0
17	1.4226E+05	2.9675E+05	1.5388E+06	78102.0
18	1.4226E+05	2.9675E+05	1.5388E+06	78102.0
19	1.4226E+05	2.9675E+05	1.5388E+06	78102.0
20	1.4609E+05	2.9675E+05	1.5388E+06	78102.0
21	1.4609E+05	2.9675E+05	1.5388E+06	78102.0
22	1.3893E+05	2.9675E+05	1.5404E+06	78102.0
23	1.3694E+05	2.9637E+05	1.5404E+06	78102.0
24	1.3660E+05	2.9713E+05	1.5404E+06	78102.0
25	1.3660E+05	2.9675E+05	1.5404E+06	78102.0

On Time Tons of:

Run No.	NATO Combat Support	NATO Combat Services Support	NATO Resupply	NATO Ammunition
26	1.3660E+05	2.9675E+05	1.5404E+06	78102.0
27	1.3577E+05	2.9675E+05	1.5404E+06	78102.0
28	1.3927E+05	2.9675E+05	1.5404E+06	78102.0
29	1.3727E+05	3.0434E+05	1.5404E+06	78102.0
30	1.3727E+05	2.9865E+05	1.2976E+06	78102.0
31	1.3793E+05	3.0434E+05	1.5404E+06	78102.0
32	1.3760E+05	3.0434E+05	1.5404E+06	78102.0
33	1.3444E+05	2.7474E+05	1.2727E+06	71385.2
34	1.3677E+05	3.0282E+05	1.5404E+06	78102.0
35	1.3793E+05	3.0320E+05	1.5404E+06	78102.0
36	1.3827E+05	3.0700E+05	1.5404E+06	78102.0
37	1.3827E+05	3.0700E+05	1.5404E+06	78102.0
38	1.3511E+05	3.0738E+05	1.5404E+06	78102.0
39	1.3627E+05	3.0738E+05	1.5404E+06	78102.0
40	1.3627E+05	3.0738E+05	1.5404E+06	78102.0
41	1.3827E+05	3.1497E+05	1.5326E+06	78102.0
42	1.3827E+05	3.1610E+05	1.5326E+06	78102.0
43	1.3893E+05	3.1762E+05	1.5357E+06	78102.0
44	1.3893E+05	3.1762E+05	1.5357E+06	78102.0
45	1.4143E+05	3.1041E+05	1.5326E+06	78102.0
46	1.4143E+05	3.1041E+05	1.5326E+06	78102.0
47	1.4143E+05	3.1041E+05	1.5357E+06	78102.0
48	1.4043E+05	3.1421E+05	1.5388E+06	78102.0
49	1.3993E+05	3.1345E+05	1.5357E+06	78102.0

Table 48. Levels of Aircraft and Ships for Output Analysis

Level	Ships	C-141	C-5	C-17	KC-10	WB CRAF	NB CRAF
1	825	160	86	150	18	100	50
2	875	172	90	160	25	108	61
3	925	184	94	170	32	116	72
4	975	196	98	180	39	124	83
5	1025	208	102	190	46	132	94
6	1075	220	106	200	53	140	105
7	1125	232	110	210	60	148	116

Note: Levels 1 to 7 correspond to -3 to +3 for Aircraft in Figure 3. The change is to help distinguish Aircraft levels from Ship levels on the graph.

Appendix E

Table 49. Aircraft Data Used for Simulation (AFP 76-2)

Aircraft Average Speed and Payload for 3500 NM Trip and Return

Aircraft Type	Average Speed (Knots)	Maximum Payload (Tons)	CRAF Aircraft Mix
C-141	401	26.6	-
C-5	427	95.7 *	-
C-17	465	83.0	-
KC-10	465	83.0	-
WB CRAF CARGO	460	79.3	B-747 200C
NB CRAF CARGO	450	32.8	DC-8 63F
CRAF WB PASSENGER	460	304 (PAX)	B-747 200C, L-1011 DC-10 30CF

* Reflects New Wartime GW = 840,000 lbs

Appendix F

Table 50. Ship Data used in Simulation

Type	Number	
BREK BULK	409	
ROLL ON/ ROLL OFF	104	
CONTAINER/ ROLL ON/ ROLL OFF	27	
CONTAINER (40 KNOT)	75	
MODIFIED CONTAINER	35	
CONTAINER	140	
BARGE	26	
FSS (SL7)	8	
CONTAINER/ BREK BULK	21	
TAC SHIP	12	
TAK SHIP	13	
CONTAINER (20 KNOT)	63	
	975	TOTAL

Cargo Type	# Movements	Moved	Unmoved	% Movements	% Tons	% Late	3 day	7 day	% Sea	% Air	AvgDaysLate
Southwest Asia											
AF	666	52083	156	0.283	0.027	0.827	0.123	0.044	0.000	1.000	1.900
ABN	39	34464	0	0.015	0.018	0.858	0.236	0.000	0.000	1.000	2.200
ARM/MECH	53	85758	0	0.021	0.045	0.000	0.000	0.000	1.000	0.000	0.000
AMBL	15	17319	0	0.006	0.009	1.000	1.000	0.000	1.000	0.000	4.400
INFANTRY	63	69933	0	0.025	0.037	0.893	0.727	0.000	0.727	0.273	4.400
PREPO	119	507	0	0.047	0.000	0.716	0.142	0.024	0.083	0.917	2.100
COMSPT	242	128412	0	0.096	0.067	0.523	0.269	0.004	0.886	0.114	1.900
CSS	545	295347	24150	0.215	0.155	0.127	0.059	0.028	0.956	0.044	0.500
MARINES	146	23706	0	0.058	0.012	0.870	0.474	0.000	0.382	0.818	3.400
NAVY	97	7950	720	0.038	0.004	0.513	0.237	0.147	0.690	0.310	2.400
RESUPPLY	531	1188557	2367079	0.210	0.822	0.052	0.014	0.000	0.951	0.049	0.100
AMMUNTON	16	7314	22179	0.006	0.004	0.000	0.000	0.000	1.000	0.000	0.000
TOTALS	2532	1911350	2414284			0.175	0.086	0.006	0.891	0.109	
NATO											
AF	693	44808	1866	0.218	0.016	0.540	0.010	0.007	0.000	1.000	1.000
ABN	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ARM/MECH	298	332340	113193	0.094	0.117	0.112	0.000	0.000	0.895	0.105	0.200
AMBL	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
INFANTRY	130	172422	16824	0.041	0.060	0.063	0.000	0.000	0.900	0.100	0.100
PREPO	237	20013	0	0.075	0.007	0.541	0.000	0.000	0.000	1.000	1.000
COMSPT	350	166386	68145	0.110	0.058	0.129	0.002	0.002	0.440	0.560	0.300
CSS	626	379476	28479	0.197	0.133	0.168	0.001	0.000	0.537	0.463	0.300
MARINES	103	59544	13122	0.032	0.021	0.097	0.000	0.000	0.817	0.183	0.100
NAVY	189	43050	6309	0.060	0.015	0.462	0.097	0.000	0.920	0.080	1.400
RESUPPLY	476	1555929	7437487	0.150	0.548	0.010	0.003	0.000	0.846	0.154	0.000
AMMUNTON	72	78102	58767	0.023	0.027	0.000	0.000	0.000	1.000	0.000	0.000
TOTALS	3174	2852070	7744192			0.074	0.004	0	0.776	0.224	

Appendix G. Sample Minotaur Run Report

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This thesis explores the possible uses of the MINOTAUR mobility model in evaluating strategic lift. Specifically, a response surface is developed for MINOTAUR which examines the effects of varying levels of aircraft and mobilization warning time on strategic lift. Four aggregate measures of effectiveness are proposed and tested for validity.

Multivariate analysis is used to explore the true dimensionality of the four aggregate MOEs as well as twelve other model output measures. Assessments are made as to the underlying factors which give rise to the measures of effectiveness, and the validity of those measures.

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